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# System Design of an Analytical Model for Health Self-Care Based on System Dynamics: Implementation and Case Study in Obesity

Gheorghe Mugur Bacioiu  
*University of Windsor*

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System Design of an Analytical Model for Health Self-Care Based on System Dynamics:  
Implementation and Case Study in Obesity

by

Gheorghe M. Bacioiu

A Dissertation  
Submitted to the Faculty of Graduate Studies  
through the Department of Industrial and Manufacturing Systems Engineering  
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Windsor, Ontario, Canada

2011

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by

Gheorghe M. Bacioiu

APPROVED BY:

---

Dr. Darek Ceglarek

Department of Industrial and Systems Engineering, University of Warwick (UK)

---

Dr. Mike Wang

Department of Industrial and Manufacturing Systems Engineering

---

Dr. Maher ElMasri

Department of Nursing

---

Dr. Jill Urbanic

Department of Industrial and Manufacturing Systems Engineering

---

Dr. Sarah Woodruff

Faculty of Human Kinetics

---

Dr. Zbigniew Pasek, Advisor

Department of Industrial and Manufacturing Systems Engineering

---

Dr. Sirinart Ananvoranich, Chair of Defense

Department of Chemistry & Biochemistry

December 15, 2011

## **DECLARATION OF ORIGINALITY**

I hereby certify that I am the sole author of this dissertation and that no part of this dissertation has been published or submitted for publication.

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## **ABSTRACT**

The initial idea for this research effort was inspired more than 4 years ago, while working to improve the Emergency Department in a local hospital. On one hand, there was the notable struggle by the medical personnel not only to cope with an unimaginable number of technical and personnel problems, but also to maintain a high standard of care. And of most significance, there was the confusion at all levels of government when called to answer the repetitive questions of “How can we change the system?” and “What can be done to save the system from collapsing?”

One potential way of easing the demand and cost is to partially shift the responsibility for healthcare to patients themselves. To do so effectively, some health management tools are required. This dissertation deals with the systematic development of a modeling tool that will track, monitor and eventually enable the development of strategies on an individual level related to body weight maintenance, loss and/or gain.

Out of all the lifestyle related diseases, this work focuses on an increasingly wide spread preventable condition termed “obesity”. Despite a multitude of studies related to obesity, neither thorough understanding nor comprehensive models have been developed.

A systematic approach based on Quality Function Deployment (QFD), allows for the development of appropriate modelling characteristics to assure quality in the outcomes, when used to manage individual's health status. Using System Dynamics (SD) and existing fractional models, a comprehensive causal model for obesity/weight was developed. This required an understanding of the relationships among the fractional

models in order to add links and feedback loops that can simulate the human body responses with certain accuracy.

The model is verified by using the real life data provided by a clinic specializing in weight management and obesity control. Based on the data, sensitivity analysis was performed, as well as a variety of scenario analyses.

Assuming that certain conditions are met, the model developed through this work can predict weight changes using energy balance information as well as an individual's characteristics with an accuracy greater than 90%.

## **DEDICATION**

To my most precious treasures, Nicole, Alex and Emma, for all they had to give up in order to make this possible. My love for you will last forever.

## **ACKNOWLEDGEMENTS**

It has been a tremendous journey, not often an easy one, but always rewarding. After looking back, I realized that I did not know how far to go for offering acknowledgements. It would be easy to look no farther than 5 years back when my passion for teaching guided me to pursue my dream, by taking on this new challenge that for many seemed senseless. However, that would not be fair to many of my family members, friends and mentors who helped make me the person I am today. It is to all those that will not be identified here that I would like to initiate my recognition and gratitude for touching my life in ways that encouraged me to continuously attempt my best in everything I do.

I am forever deeply grateful to my advisor, Dr. Zbigniew Pasek, PhD for finding ways to deal with me and my persistent stubbornness. As a true mentor, he did not want to create my journey but rather let me explore the opportunities until finding it on my own. Dr. Pasek's wisdom, patience and insight guided me to shift in the right direction, even though I struggled to immediately visualize the goal. He had the strength to demand performance and high standards without compromises, while remaining flexible in allowing me to find my way at meeting these demands.

I am also indebted to my diverse dissertation committee which include Drs. Michael Wang, PhD and Jill Urbanic, PhD from IMSE, Dr. El-Masri, PhD from the Faculty of Nursing, and Dr. Sarah Woodruff, PhD from the Faculty of Human Kinetics for keeping me focused with my feet on the ground. The array of knowledge spanning



from engineering to nursing to human kinetics, as well as the ideal mix of personalities, were of great support at critical points in my journey.

I am thankful to Dr. Darek Ceglarek, Director, Digital Lifecycle Management, Warwick University for accepting to be my External Examiner. I was impressed a few years ago with the excellence in research emerging from the center he continues to manage. It is an honour having such an experienced researcher reviewing my dissertation.

It is impossible to identify all professors, staff members and students that supported me in the last 5 years. I am thankful to Drs. Bussiere, PhD and Gowing, PhD from OSB for having such a deep trust by allowing me to do what I love the most, and that is teaching. I will remember all the friendship developed in the IMSE and OSB departments that made many of my difficult days a lot easier. Their efforts were priceless and ever so timely when I needed them the most.

My gratitude goes also to a special friend of mine, Sean McCann, MSc whose mentorship and guidance helped me tremendously. I am thankful for the many hours Sean spent providing feedback to my research. Without his input, my efforts would not have been what they are today.

I also want to recognize and thank Dennis MacDonald and Ed Bernard from Windsor Medical Weight Loss Clinic who were willing to not only discuss with me some of the clinical and non-clinical aspects of their work, but also provided me with real life data that I used for assessing the accuracy and other aspects of my model.

No words can describe the feelings to my dear parents. Although far away from each other, I know how much this means to them. Thank you for a life of love and care and for all you had to give up, allowing me the best opportunities for becoming a

professional. My love and gratitude go also to my lovely sister, Crina, my brother-in-law, Bogdan and my niece Dorulea for their support and for giving me their insight when I needed the most. Thank you!

Last but not least, I am deeply thankful to my lovely wife, Nicole, and to my wonderful children, Alex and Emma. It is their trust, love and support that inspired me to always hope for a better future. Without their continuous support beside me, understanding the challenges and traversing the unavoidable bumps on the road of life as a true family, I would not have found the energy to complete today's task at hand. I love you all so much.

In the end, I apologize again to all the other individuals that have contributed, directly or indirectly, to help me achieve my research and personal goals. I assure you all that you will always remain in my heart and live in my memories.

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## **LIST OF ACRONYMS**

AMHSC	Analytical Model for Health Self-Care
ANOVA	Analysis of Variance
BM	Body Mass
BMI	Body Mass Index
BMR	Basal Metabolic Rate
BREQ	Behavioral Regulation in Exercise Questionnaire
CAPCH	Canadian Association for People-Centered Health
CM	Change Management
CTS	Critical to Satisfaction
D	Diet
DES	Discrete Event Simulation
E	Education
EB"X"	Evidence Based "X"
EBDM	Evidence Based Decision Making
EE	Energy Expenditure
EER	Estimated Energy Requirement
EI	Energy Intake
FA	Fitness Activity
FFM	Fat Free Mass
FH	Family History
FM	Fat Mass

FR	Functional Requirements
HOQ	House of Quality
IC	Individual Characteristics
LM	Lean Mass
MVSS	Multivariate Sensitivity Simulation
NPF	Non-Physical Factor
OS	Obesity System
PA	Physical Activity
PAF	Physical Activity Factor
PAL	Physical Activity Level
PE	Physical Environment
PG	Personal Genomics
QFD	Quality Function Deployment
RN	Random Normal
SD	Systems Dynamics
TEE	Total Energy Expenditure
TF	Transfer Function
TRMR	Resting Metabolic Rate
VIF	Variation Inflation Factor
VoC	Voice of the Customer

# CHAPTER I

## INTRODUCTION AND PROBLEM DEFINITION

### 1.1. Healthcare Crisis and Contributing Trends

Between the years 2000 to 2008, the Canadian population grew less than 5% from under 31 million to over 33 million individuals. At the same time, the total personal expenditures on medical care and health services increased continuously in the last 8 years by more than 70%, from \$29 billion in 2000 to \$38 billion in 2004 then surpassing the \$50 billion threshold in 2008 (Statistics Canada, 2010). When the population and expenditure data are plotted together (Figure 1), the situation is even more evident, due to the accelerated growth in healthcare expenses relative to the slower population growth.

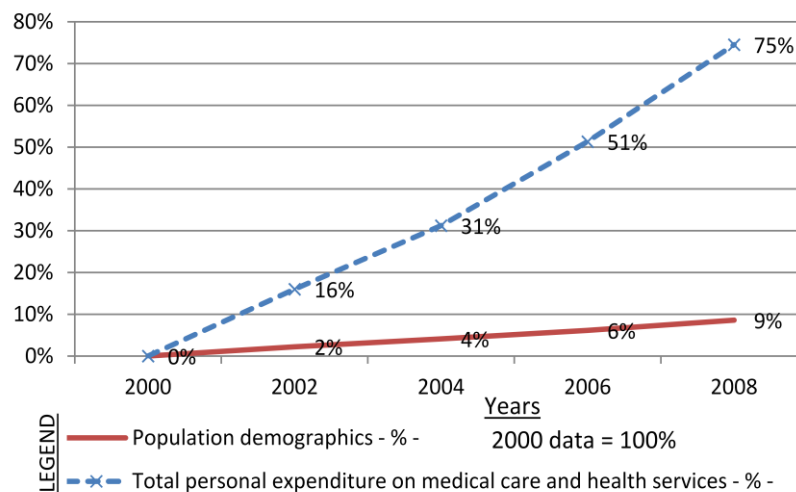


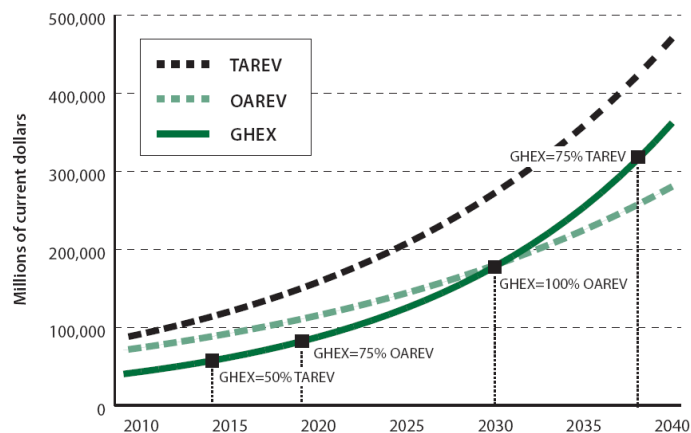
Figure 1 - Canadian Population vs. Healthcare Expenditures 2000-2008

One of the main concerns with this healthcare trend is related to future Canadian population increases. It is estimated that when comparing with the data for 2011, the Canadian population will increase by another 11.7% in 2026 and 15.1% by 2031 (Statistics Canada, 2010). The demand for the healthcare services will substantially

increase relative to the Canadian population growth, especially when the trend observed in Figure 1 is taken into account (Statistics Canada, 2010). This is further accentuated when longer life spans are expected (Ministry of Finance, 2010).

According to an extensive study by IBM (2006) in Ontario as Canada's most populous province, if solutions are not found, healthcare will account for 50 percent of governmental spending by 2011, 67% by 2017, and 100% by 2026. According to the Ministry of Finance (2010), the healthcare spending in 2009 accounted for 45% of the total budget of the province.

Figure 2 (Rovere & Skinner, 2010), is shows the 10-year projection for the three important indicators of Government Health Expenditures (GHEX), Total Available Revenue (TAREV), and Total Available Own Source Revenue (OAREV). All indicate alarming trends. These projections indicate that if Ontario does not significantly restructure the way it finances healthcare, then healthcare spending will consume 75% and 100% of the province's own-source revenue by 2019 and 2030, respectively.



Source: Skinner and Rovere, 2009.

Figure 2 - Healthcare Expenditure Trend in Ontario

According to the Ministry of Finance (2011), the following actions are planned for controlling healthcare spending:

- The government is reducing the time that patients in the hospital must wait before moving to a long-term care home or other more appropriate settings, through increased funding for long-term care homes, home care and other community supports, assisted living services, and mental health and addiction services. These investments will help manage down costly acute care pressures.
- As a result of the Excellent Care for All Act of 2010, hospitals are now required to develop and post annual quality improvement plans, where the compensation of health care executives is directly linked to achieving the plan targets.
- The government has been modernizing the Ontario Health Insurance Plan (OHIP) to ensure funding is directed to where medical evidence shows the greatest value without compromising access to services. Since 2010, evidence-based changes to OHIP services have saved the health care system more than \$150 million without affecting patient care.
- Measures include curbing unnecessary testing and promoting procedures that reflect technological advances.
- Recent reforms to Ontario's drug system are keeping drugs affordable. This is important because pharmaceuticals have been one of the fastest-growing areas in the health care budget. These reforms are saving approximately \$500 million a year, which is being reinvested back into health care services.

In (Health Canada, 2005) it is mentioned that the federal Public Health Agency of Canada acts as a focal point for disease prevention and control. The federal government is also responsible for health protection and regulation (e.g., regulation of pharmaceuticals, food and medical devices), consumer safety, and disease surveillance and prevention, and provides support for health promotion and health research.

The importance of preventive medicine was recognized a long time ago. According to (Beall, 1882) in what is arguably one of the first public recognitions of the importance of preventive medicine as “the highest department of the art of the physician.” A facsimile of an excerpt from the essay published more than 100 years ago (Beall, 1882) is presented as Figure 3.

**The importance of my subject is self-evident. If the science of medicine, when applied to the healing of disease, is one of the noblest to which man can devote his time and talents, how much nobler is it when it strives to invade the strongholds of disease, and, by restricting and limiting the avenues through which it makes its attacks, adds immensely to the wealth, prosperity, and happiness of mankind. Preventive Medicine is indeed “the highest department of the art of the physician.”**

Figure 3 - Paragraph from Beall’s Essay

To a better understanding the impact of preventable diseases relative to the population mortality rates, a search for data specific to preventable diseases was performed. Table 1 (Danaei, et al., 2009) provides the data for deaths from all causes (thousands) attributable to different risk factors and the 95% confidence intervals for their sampling uncertainty in Canada.

Table 1 - Deaths from all Causes (thousands) Attributable to Risk Factors

Risk factor	Male	Female	Both Sexes
Tobacco smoking	248 (226–269)	219 (196–244)	467 (436–500)
High blood pressure	164 (153–175)	231 (213–249)	395 (372–414)
Overweight–obesity (high BMI)	114 (95–128)	102 (80–119)	216 (188–237)
Physical inactivity	88 (72–105)	103 (80–128)	191 (164–222)
High blood glucose	102 (80–122)	89 (69–108)	190 (163–217)
High LDL cholesterol	60 (42–70)	53 (44–59)	113 (94–124)
High dietary salt (sodium)	49 (46–51)	54 (50–57)	102 (97–107)
Low dietary omega-3 fatty acids (seafood)	45 (37–52)	39 (31–47)	84 (72–96)
High dietary trans fatty acids	46 (33–58)	35 (23–46)	82 (63–97)
Alcohol use <sup>a</sup>	45 (32–49)	20 (17–22)	64 (51–69)
Low intake of fruits and vegetables	33 (23–45)	24 (15–36)	58 (44–74)
Low dietary polyunsaturated fatty acids (PUFA) (in replacement of SFA)	9 (6–12)	6 (3–9)	15 (11–20)

The work presented in this thesis is focused on proposing an approach for System Design of an Analytical Model for Health Self-Care Based on System Dynamics: Implementation and Case Study in Obesity (AMHSC).

If the impact of overweight-obesity and physical inactivity are evaluated relative to the number of deaths (since both are direct risk factors related to obesity overall), together they are the second most common cause of death immediately behind smoking. However, the impact can be even more significant if the indirect impact of obesity from other categories is considered (e.g., high blood pressure, dietary trans-fatty acids, etc.).

Society has come a long way in finding cures for many diseases through administering vaccinations, medications and other means. Most of this progress is attributable to the advancements made by professionals in medicine, science, technology, engineering and economics. What has arguably been missing from the research focus is the prevention of diseases through individuals taking a conscious responsibility for their health behaviour rather than all the advancements and progress mentioned above. The prevailing mindset is that the doctors, nurses and healthcare professionals are generally indispensable, being both responsible and accountable for the health of each patient. The



reality is that beyond the beliefs related to responsibility, accountability and ownership, the human population both reaps the benefits of a robust system as a whole, or suffers consequences as ailing individuals.

The approach proposed by this work supports the prevention part of the healthcare system. The long term vision for this work is by no means unique. Presented on the main page of the Canadian Association for People-Centered Health (CAPCH) website, their vision is clearly identifiable as, “The CAPCH is founded on the belief that the Canadian Health System should inform, empower and support each person as the manager of their well-being and that all Canadians should have access to a defined, publicly-funded level of care and service.” (CAPCH, 2011)

It is very difficult to envision a stable healthcare system in the future unless feasible solutions for the current problems are developed (Morrison, 2000). The main challenge is to define realistic, feasible and universally available solutions that can account for various dynamic trends in the future. Can healthcare accommodate these changes?

## 1.2. Potential Solutions

Due to the uniqueness of the Canadian healthcare system that guarantees full healthcare access to the entire population, one possible solution is the rationalization of it. This means that the system through its owners (population at large) and representatives (Government) should discourage the overutilization of this critical and limited shared resource by defining proper means for the allocation of the resources when and where needed.

Another challenge for the overall system is related to the growing cost escalation discussed in Chapter 1.1. While system optimization solutions have been implemented (Department of Health and Human Services, 2011) and are currently a focus of the decision makers, cost-saving potential of the prevention component of the system has not been effectively tapped yet. When considering the obesity as the example used in this work, life-style changes can fundamentally modify the current allocation of the healthcare resources. If making a conservative estimate by considering an average spending of \$5,500/person (Canadian Institute for Health Information, 2010) and approximately 50% of the Canadian population currently being overweight or obese (McLeod Lyn, 2010), a 5% reduction in expenditures equates to over \$4 billion in annual savings.

Of the four healthcare components presented in Figure 4, prevention supports both, the effort of transforming the healthcare system and the primary need of the population from a human perspective to prevent and maintain a healthy life. The fourth component is the inherent self-regulation, and involves the body's internal mechanisms for adjusting to the environment and any attempts of being taken out of equilibrium. While the human body is extremely versatile in maintaining and adjusting continuously to external stimuli, there is a limit beyond which the self-regulating mechanism fails to adjust.

The prevention component of Figure 4 supports the two most evident conditions of acute and chronic illnesses, in the sense that preventing diseases from occurring averts an individual from transferring to one of the other two categories. It also complements

the internal system by increasing its capacity of adjusting or mediating conditions before they become critical, and require a self-adjusting intervention by the human body.

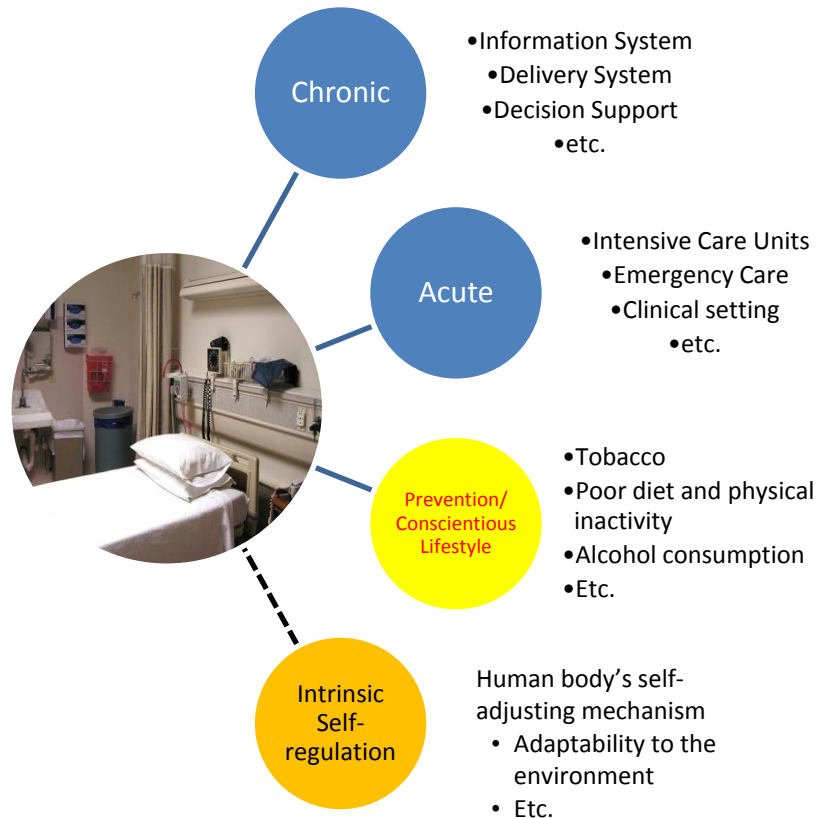


Figure 4 - Healthcare Components

A 2010 report on Ontario's health system (McLeod Lyn, 2010) notes that among other root causes for quality problems, is the patient's disengagement from their own care. They often do not follow physicians' advice on lifestyle or treatments and frequently are unwilling or unable to adopt proper lifestyle changes. They may find it too confusing to take all the recommended tests or drugs. Or they may believe that it is too expensive to eat a healthy diet. Also, patients may not enjoy exercise or think it is too expensive. The AMHSC may often then support not only in the decision making process but also allows them to become the major drivers of the process. The patients will be

engaged in their healthcare prevention and make the necessary changes related to their own situation.

The conceptual graph in Figure 5 illustrates the importance of the preventive approach when considering the cost associated compared to therapeutic (when a condition is present) or even maintenance (condition is fully controlled when present).

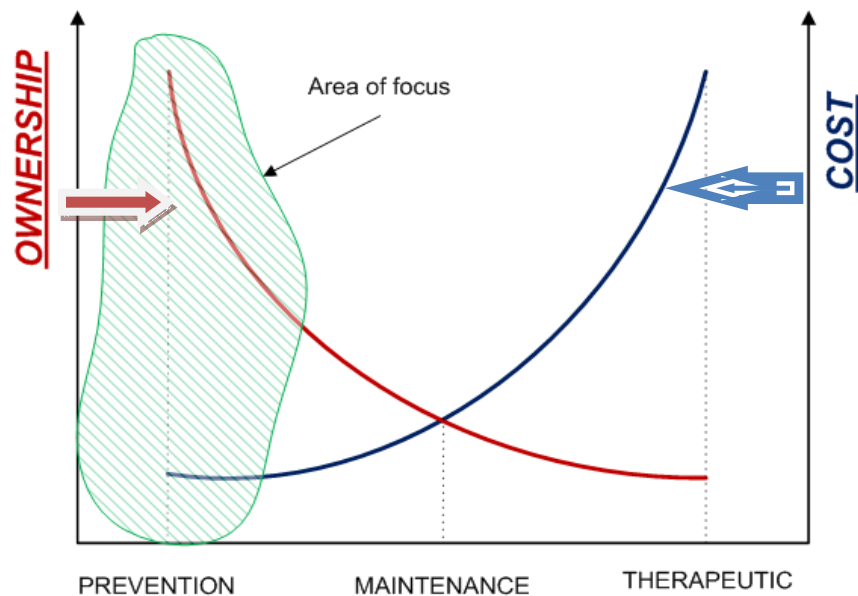


Figure 5 – Area of Interest with Respect to Treatment Cost

Prevention has also been identified for many years as a major cost control component in the industry. A noted industrial quality expert, Joseph M. Juran, has advocated a cost-of-quality accounting system to convince top management of the need to address quality issues. He identified four categories of cost including: internal failure costs (from defects discovered before shipment), external failure costs (from defects discovered after shipment), detection costs (for inspection of purchased materials and during manufacture), and prevention costs (for keeping defects from occurring in the first

place). Juran found that in most manufacturing companies, external and internal failure costs together accounted for 50 to 80% of the total cost of quality. Thus to minimize this total cost, he advocated that more attention be paid to prevention. Suggestions have been made that every \$1 invested in prevention is worth \$100 in detection costs and \$10,000 in failure costs (Juran & Gryna, 1980).

If this is factually true in industry, what makes stakeholders believe that is not a critical consideration for healthcare? Bearing in mind the consequences of failures in healthcare, it is arguable that it is drastically more impactful from a cost perspective if prevention is considered and promoted versus any other solution to reduce costs. This is confirmed by a USA Governmental report (U.S. Department of Health and Human Services, 2003) that states, “There is clear evidence that the costs of chronic conditions are enormous, as are the potential savings from preventing them, even if there may not always be agreement on the exact amounts of these costs and savings.”

### 1.3. Needed Enablers

(McLeod Lyn, 2010) suggests solutions for addressing the root causes in Ontario’s healthcare system such as: teach patient self-management, create written instructions or simple checklists, promote lifestyle changes, and create healthy communities.

Canadian Association for People-Centred Health (CAPCH, 2011) has defined four key principles comprised of ten critical elements that are necessary conditions for Canadians to truly have a people-centred health and wellness system, and is described as follows:

1. Responsibility – People are responsible for their health and wellness. This principle is comprised of three key elements:

- Ownership – People own the realities and determinants of their personal health and wellness, and their need for health care services.
- Empowerment - People empower themselves and can be further empowered by health care professionals to manage their health and wellness.
- Commitment – People strive to improve their health and wellness.

2. Autonomy – People make their own decisions that affect their health and wellness. This principle is comprised of three key elements:

- Individuality – People’s individuality and definitions of health care quality are respected.
- Authority – People have the authority to manage any or all aspects of their health and wellness, and delegate that authority to someone else.
- Choice – People have the right to know and choose among all available options on how best to manage their health and wellness.

3. Informed Health Management – People have the information needed to manage and make informed decisions about their health and wellness. This principle has three key elements:

- Personal Health Information – People own their personal health information. This is defined as personal health records and information about alternative treatment options.
- Access – People have access to their personal health information at all times. This information is clear and understandable.

- Privacy – People’s health information is private. They have the right to share it with whomsoever they choose.

4. Partnership – People partner with healthcare providers to ensure the best possible outcomes. This principle has one very important element:

- Support – People receive the support they require to take responsibility and ownership of their personal health, to access their information and to make decisions concerning the options available to them. Health care professionals collaborate with one another to provide the best possible health care and wellness options, and services to the people they serve.

While the intent is in having eventually all four principles under complete control of the individuals, support is needed in order to make the transition to a patient-centered system possible. The lack of health management tools for individual or personal use is one of the key issues. The work performed through this research is directly supporting several points presented above. Through discussing the first principle (Responsibility), in order to facilitate a change in ownership, as well as the ability to be empowered, a decision support system is required. The tool proposed by this work supports both the empowerment, as well as the ownership since it incorporates the information required to facilitate the transition.

Other principles directly addressed by the AMHSC methodology and the tool proposed in this research include: Individuality (the tool is customizable for each individual), Authority (individual owns the tool and they will have full authority in how to use it), Choice (strategy will depend on the choice that the individual makes), Personal Health Information, Access and Privacy (fulfilled in case the tool is used for personal use

and by the owner), Partnership (tool is used in collaboration with healthcare professionals that can easily monitor the progress remotely).

While the AMHSC addresses, to a point, the health status condition management and maintenance, the main benefit and focus of the proposed system is in supporting various comprehensive measures. A major success factor of such a system is in its ability to adjust for each individual.

#### 1.4. Problem Formulation

The healthcare trends and the growing costs presented in Chapter 1.1 have forced the Canadian government to take notice and propose measures of improvement (Department of Health and Human Services, 2011). At this point in time, the effects of these measures are not yet known.

Out of their four principles listed by the Canadian Association for People-Centred Health (CAPCH, 2011), the individual's responsibility and self-governance are somewhat neglected, and are not considered to be a key part of the solution. Arguably, the lack of health management tools for individuals to use is one important element that hinders their ability to gain understanding and eventually take responsibility and ownership of their healthcare prevention.

From the list of preventable conditions (U.S. Department of Health and Human Services, 2003), obesity (Raine, 2004) was chosen as a key issue that allows this research to be focused. The development and implementation of a robust system for individual management of obesity would not only support the fight against it, but it would also provide a significant relief to the overall healthcare system in the long term. This would



be achieved by reducing visits to doctors for situations directly related to the obese condition, or indirectly by other preventable ailments that can be reduced just by addressing the obesity problem (e.g., hypertension, diabetes, joint replacements, etc.).

(Lassard, 2006) provides a comprehensive report by bringing forward some healthcare realities into this millennium, as follows:

- Significant increase in the combined overweight/obesity occurrence among youth aged 12 to 17 in the last 25 years.
- Increase in obesity among adults 18 years and older from 14% in 1978 to 23% in 2004.
- Increase significantly, for overweight and obese individuals, of risk for a range of preventable chronic diseases, including but not limited to cardiovascular disease, hypertension, type-2 diabetes, arthritis and some types of cancer.
- The total number of deaths in Canada related to overweight and obesity from 1985 to 2000 was more than 57,000 (about 2% of the total number of deaths), according to research estimates (Statistics Canada, 2005).
- The total direct cost of weight-related major chronic diseases to Canada's health system was nearly \$1.6 billion in 2001. Coupled with indirect costs, this total was \$4.3 billion out of a total annual healthcare expenditure of almost \$70 billion (6.1%).

The new guidance on the prevention of type-2 diabetes in adults published recently (Lancet, 2011), makes 11 recommendations, mostly on how commissioners and providers of public health services can best convey messages to promote behaviours that reducing diabetes and the associated harms. The key recommendations are the promotion

of healthy diets and physical activity, which is hardly surprising. In a comprehensive report issued by the European Observatory on Health Systems and Policies (Marchildon, 2005), it is concluded that more Canadians are obese today than in the past, creating a myriad of health problems for the individuals affected, and growing demands on the health system in general. In 2003 within Canada, approximately 7.9 million adults aged 18 and older were overweight, and roughly 3.5 million were obese. This means that approximately 25% of the Canadian population is overweight, while approximately 11% is obese. Moreover, obesity is becoming more prevalent among Canadian children, which is a situation with dire implications for the longer term.

The obesity pandemic is, at a minimum, a persistent yet complex problem to solve. It has been the focus of many organizations, including government, university research, pharmaceutical industry, etc. While considerable research has been done, the information is fragmented, which leads to an inconsistent understanding of the causal loop.

This work is instrumental for assembling some of the pieces together and building a system dynamics based model with dual use, as follows:

- In a clinical setting, supporting individuals that are already considered obese
- In a preventive setting, enabling development of alternative strategies for individuals so they can remain within healthy weight limits

By recognizing the complexity of the obesity condition, the process of building and integrating a consistent body of knowledge will provide a reliable and widely valid decision support tool for continued exploration of the topic in the future.

### 1.5. Proposed Approach

This work is employing a multi-disciplinary approach, and uses some of the best tools each field has to offer in support of designing and building a health management tool for individual and/or personal use in the fight against obesity.

A system design methodology allowing seamless integration of the necessary components is based on System Design concepts (Akao, 1990) concepts. Another major element of this work is in the area of prevention, with a particular focus on obesity. The link between the two and the foundation for both, supporting the decision making process (Parnell, Driscoll, & Henderson, 2011), is an Evidence Based data-driven approach (Munro, 2005) (DiCenso A. G., 2005). A conceptual block diagram (Bacioiu & Pasek, 2011) is displayed in Figure 6. The multidisciplinary approach engages the three major disciplines which include: Engineering with System Design and System Dynamics modeling components; Evidence Based Theory with Decision Making and Evidence Based Interventions; and Healthcare including Health Prevention and Psychology.

The main research questions on which the study focuses are summarized as follows:

- Conceptually, what is needed and how should the health management tool be designed?
- How can synergy in the design process be achieved between the main (prevention) system and its multiple preventable diseases subsystems (i.e., obesity, blood pressure, etc.) so that the method is replicable?
- What evidence is needed to support individuals adopting the new health management tool for individual and/or personal use?

- What type of decision structure needs to be in support of the individuals adopting the AMHSC?
- What system modeling environment can be used for simulating the dynamic behaviour of the human body, particularly related to obesity?
- What other elements in the design of the system are critical for feasibility, as well as long term sustainability (e.g., environmental, emotional, etc.)?

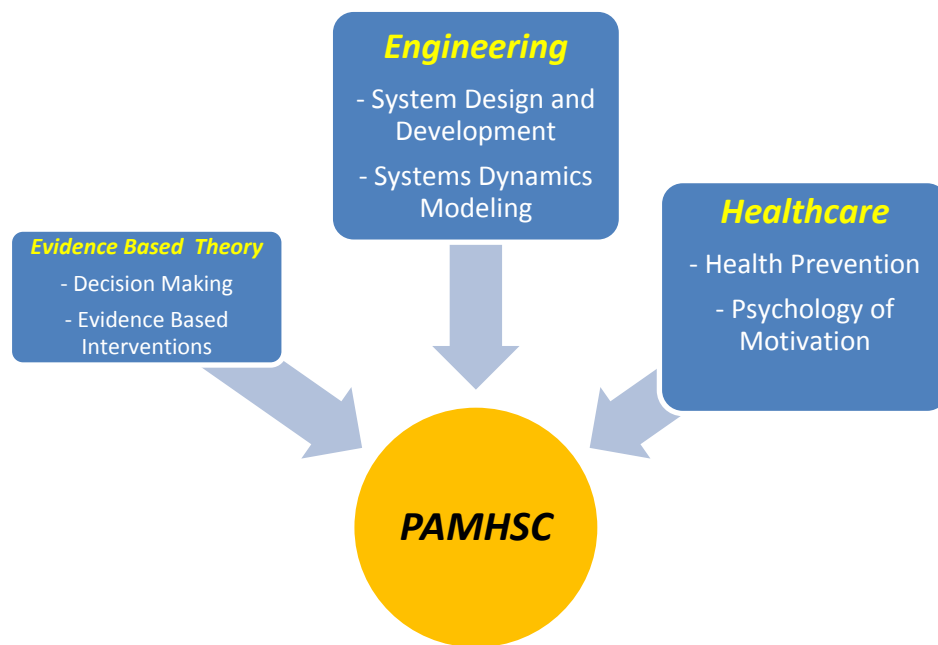


Figure 6 - Conceptual Block Diagram for AMHSC

The system particularly focuses on prevention aspects for an individuals' personal healthcare management. However, the concept is expandable to the other two modes that an individual may encounter within their life cycle, and these include routine maintenance and therapeutic.

While there are multiple tools and concepts employed throughout this work from all three main fields of research (i.e., system design and modeling, healthcare prevention,

and evidence based decision making), the core of this work evolves around the use of Quality Function Deployment (QFD), System Dynamics (SD) modeling, and Evidence Based (EB) health knowledge. Building an approach leading to a methodology based on the above mentioned elements, allows for the development of a rational model that can be tested against real life data.

This work defines the minimum requirements of the overall system, and develops the principles required to design such a health management tool. The concept is illustrated through a system simulation model, addressing obesity as one of the major medical conditions experienced by society.

Unlike the other approaches to eliminate obesity, the proposed model within the present research does not simply provide a weight loss plan. A simplistic, one-size-fits-all approach is arguably the major weakness of most other attempts for providing solutions to the obesity problem. Many of the attempts fail within months or a few years, if not immediately after a successful drop in weight is observed. In other words, the maintenance of the weight loss is not robust, considering that the person succeeds in losing the initially planned weight.

(Collins, Khoury, Morton, & Olster, 2008) suggest that now is an important time to consider whether these guidelines can be personalized using advances in genomics and related fields, and what additional research may be needed to determine how to personalize obesity interventions. For example, can some individuals be more effective in weight control by concentrating on the energy expenditure side of the equation, while others should concentrate on the energy intake side? Currently, major challenges exist in the application of personalized approaches to obesity control and prevention. Along these

lines, the system proposed by this work accounts for the difference among individuals.

This means that not only the physical differences need to be considered but also the non-physical factors (e.g., emotional, stress, etc.), as well as the difference in preferences.

The development of the model is based on the assumption that each individual is a different entity. While it is easy to find individuals of relatively similar gender, age, height and weight, it is virtually impossible to find even two individuals having identical characteristics, where twins are a notable exception.

A decision matrix (Bacioiu & Pasek, 2011) summarizing the process that an individual would follow by adopting the proposed methodology is presented as Figure 7. This decision matrix was developed based on the feedback from the system's stakeholders. A detailed introduction of the methodology is presented in Chapter III.

As a future work focus based on this research, the health management tool can be expanded both vertically and horizontally. The vertical expansion can be achieved by identifying additional transfer functions for the parameters developed during the system design process that are not implemented in the model. This will allow for greater accuracy, and probably more importantly, will permit a wider application of the model beyond a controlled, clinical type environment. It will also account for the future progress in knowledge.

A horizontal expansion can be achieved by adding other preventable conditions to the obesity concern. By using the same methodology, the critical outputs of the system design can be identified for any other condition, and they can be used as inputs to such particular models.

A far more detailed research effort can be performed by combining multiple preventable conditions in one dynamic model. This will allow for an even more realistic simulation of the prevention system, where the interactions between different conditions can be accounted for.

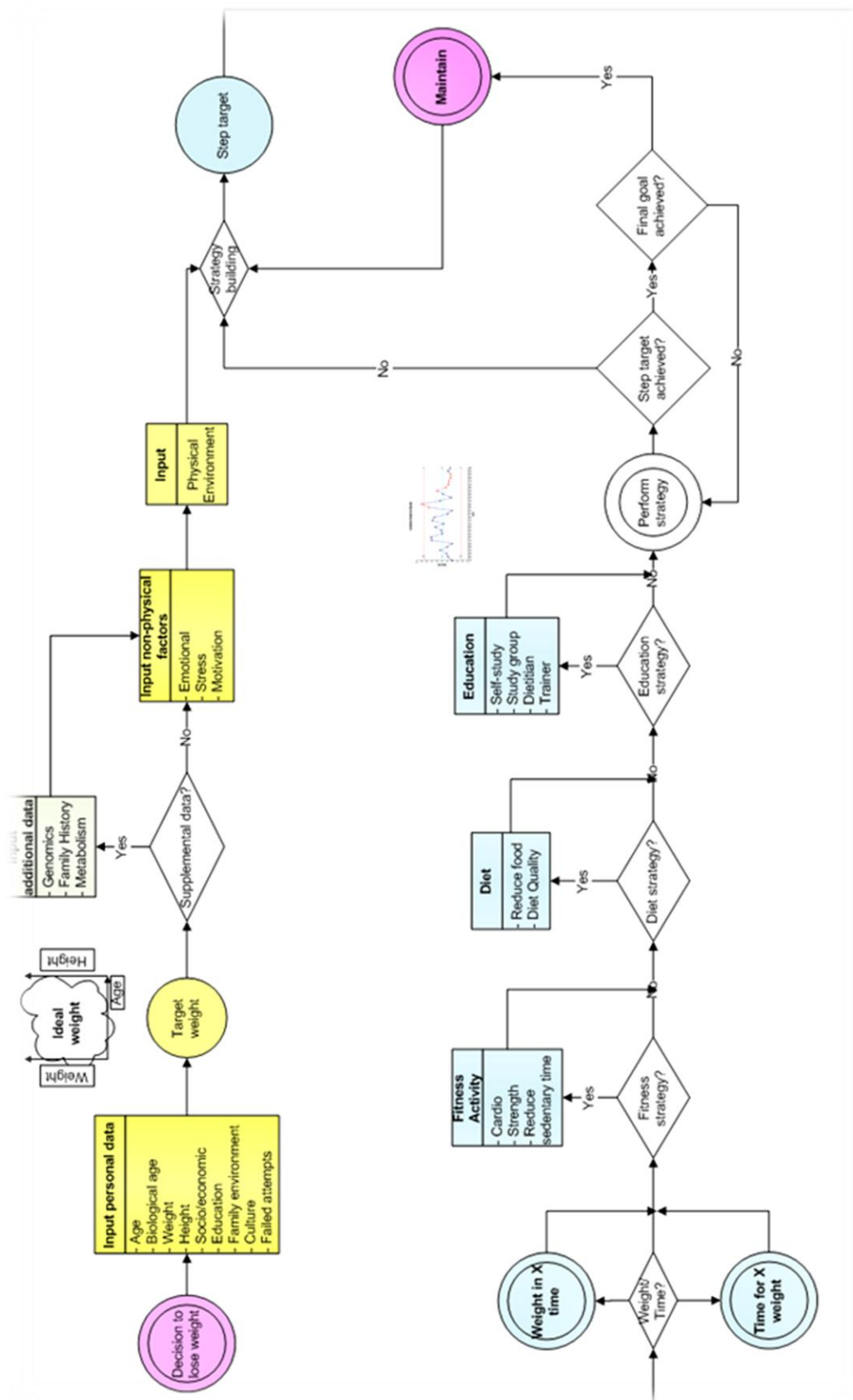


Figure 7 – Decision Process



## CHAPTER II

### REVIEW OF LITERATURE

Considering the multidisciplinary nature of this effort, diverse sources of information were required for both, a comprehensive understanding of the problem and development of a viable solution. Consequently, the necessary knowledge had to be drawn from several unrelated fields that seemingly had very little to do with each other.

This research focused also in finding the complementary strength of what are traditionally considered unrelated fields of knowledge, identifying the synergies, and developing a methodology for synchronizing the research process.

The three major fields are presented at the top of Figure 8, where this figure also provides a full outline of the literature review process. The Systems Engineering and Healthcare Prevention fields are complemented by an Evidence Based approach, with the first two legs playing a major role in the overall development. The next two levels on this figure include additional details about the Systems Engineering and Healthcare Prevention fields.

System Engineering is further split into System Design and System Modeling. For the Healthcare Prevention cluster, it is divided into Policy & Obesity Management and Psychology.

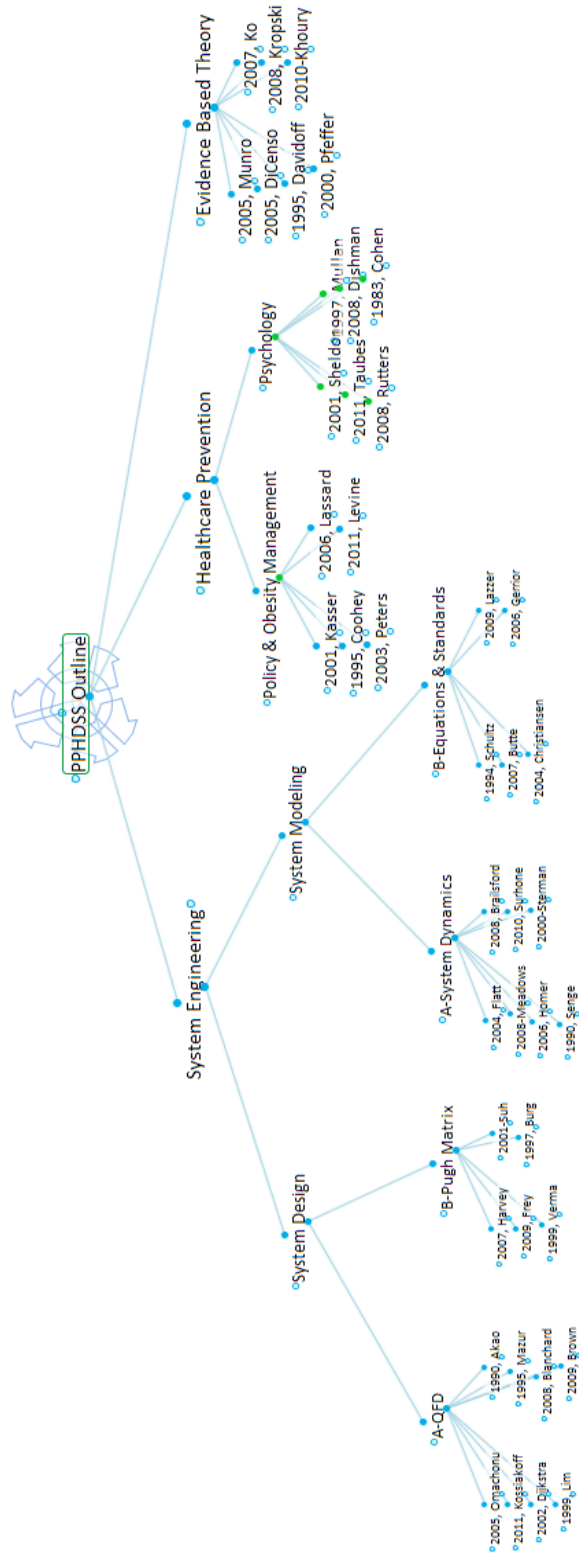


Figure 8 - AMHSC Literature Review Structure

The system development was approached from a holistic, higher level perspective rather than reducing the focus to smaller components. A similar thinking applied to a different problem in a manufacturing environment. In (Bacioiu & Pasek, 2009) an innovative approach was used in applying Quality Function Deployment (QFD) simultaneously to two sets of customer requirements in order to support the decision making process by leveraging the synergies and identify the conflicts within each and also between the two.

As this work will continue in the future, setting the foundation on a strong base is imperative so that it can be subdivided into different stages at a later date. In the first stage, not all of the major components are addressed to the same level of detail. This is not only due to the fact that there is a natural order of things in the development of any system (i.e., before beginning the system design stage, a very thorough understanding of the Voice of the Customer (VoC) is required), but also since there is the need for a certain structure to be in place before attempting to engage some of the components (i.e., testing can be performed once a functional prototype or model is available). Also, in this first stage, a higher emphasis was placed on developing the system, understanding the challenges of the obesity management, and developing the first level of the system model, all on robust evidence based approach. Both the psychological aspects, as well as the attempt to promote a different prevention policy, although engaged at a basic level, will help to establish the subject matter on more of an aggressive development stage in the future.

## 2.1. Systems Engineering

### 2.1.1. System Analysis and Design

The Systems Design category presented in Figure 8 is made up of two major components consisting of Quality Function Deployment and Pugh Matrix, where both are described separately below.

#### 2.1.1.1. Quality Function Deployment (QFD)

In the standardization of the design process, QFD is explained in detail by (Akao, 1990). QFD is one of the most powerful tools currently used for developing new products and processes based on the existing designs and, even more commonly, for new and innovative ideas. According to Akao, “we already know what quality items must be assured for existing products. With new products, we must start learning, “what to assure”. In QFD deployment, we start by attempting to understand both the latent and actually existing qualities demanded by the customers.”

In their paper (Mazur, Gibson, & Harries, 1995), the authors present two case studies to illustrate their comprehensive approach for service QFD. The authors followed the traditional steps in gathering the VoC, measures of the VoC, functional requirements, etc. One of the case studies was staged in a therapy clinic, whereas the second one was in a telephone company. They concluded that QFD can be effectively applied to service processes.

(Lim, Tang, & Jackson, 1999) explore the applicability of QFD in healthcare. The QFD technique is described and explained on how it leads to a better understanding of the customers' expectations. The authors argue that with some modifications, the QFD technique can be applied in service industries, even in labor-intensive establishments

such as hospitals. They also mention that the key differences are customer identification, procedures for the establishment of expectations, inseparability of the service offering and service delivery, and definition of the quality elements. The authors advocate that hospitals use QFD for identifying and improving the unmet patients' expectations.

In their paper (Dijkstra & van der Bij, 2002), the authors recognize the applicability of QFD in environments other than in the industrial domain. Also the authors mention that there is very little experience with the application of this tool in healthcare particularly, and other service sectors in general. Some of the challenges recognized by the authors involve the difficulty in clearly or uniquely answering the following two key questions: “Who is the customer?” and “What exactly is the product?”.

Indeed, stating that the patient is the customer, and a recovered, healthy individual is the product is simplifying the dilemma. This does not allow for the identification of a feasible solution. There are more stakeholders that need to be engaged in the decision making process including the patient’s family, insurance companies, workplace, government, etc. Ultimately, the authors suggest using the process as the actual product. This makes the approach easier and more suitable for a healthcare environment.

(Omachonu & Barach, 2005) argue that the application of the QFD in the healthcare industry has been limited because the product of healthcare is ill defined and intangible. However, QFD was successfully applied to rehabilitation and dietary services. The case presented in the article used QFD to redesign a managed care organization’s (MCO) member handbook. The authors present results similar to what would be expected in an industrial environment. In this particular case, the number of calls per day decreased from 3,000 to 1,900, or a reduction of approximately 35% due to the redesign of

handbook. However, the authors mention some drawbacks of the QFD since it assumes that an organization has the resources to overcome any constraints it may encounter in fulfilling the plan, and incorporates some subjective data as it depends mostly on qualitative analysis.

In addressing the challenge of dealing with systems that do not necessarily create a product nor do they have an identifiable customer, (Fitzsimmons & Fitzsimmons, 2010) discuss the application of design and redesign tools in the service industry. The healthcare system has many similarities with what we consider service. First and foremost, although we can consider the patients as the “products” of the system, the “product” is “serviced” rather than actually produced in the case of the healthcare system. Another similarity with the service industry is the multiple VoC. In a healthcare system, there not only is a diverse array of “customers”, but unlike in a majority of other systems, a customer is simultaneously the owner of the system. This brings different dynamics into the picture if we just compare it to a product that in general, is produced by the owner of the system and used by the customer, where typically the customer and owner are not the same individual.

The core of the system design methodology used in this research is based on (Akao, 1990) (Blanchard & Fabrycky, 2011) (Breyfogle III F. W., 2003). Arguably, the most important part of the methodology is in understanding the requirements of the system that meet the customer expectations and referred to as VoC.

While the design methods are used in various fields as the pillars for development of new product and processes, they are, in general, not commonly used for system design and analysis, particularly in healthcare system design. This work adapted some of the

design concepts for the purpose of AMHSC development and in support of the transition from the macro-system to the subsystems.

In (Blanchard, 2008), the author mentions that there is an ever-increasing need to develop and produce systems that are robust, reliable, high quality, supportable, cost-effective from a total life-cycle perspective, and responsive to the needs of the customer/user in a satisfactory manner. A closer look at the above statement through the healthcare system design perspective, demonstrates the direct applicability of the characteristics listed in general. Indeed, starting from the most recently described system design methods underscore the importance of identifying and thoroughly analyzing the VoC. The VoC needs to be complemented by a high-quality, reliable and cost-effective solution. The author also observed that a majority of the problems in system design have been a direct result of not applying a total system approach, from the beginning, in meeting the desired objectives. This means that the overall requirements for the system in question were not very well defined initially.

The work presented in this paper considers the design phase starting from a thorough understanding of the requirements at the system level before launching into the actual detailed design. (Blanchard, 2008) also suggest that the system design and development process has suffered from a lack of good, early planning, and clearly defining the requirements in a complete and methodical manner. Another challenge for the healthcare system observed by the author based on the approach taken was that it became quite costly in long term.

As presented in Figure 9 from (Blanchard, 2008), system design is an iterative approach.

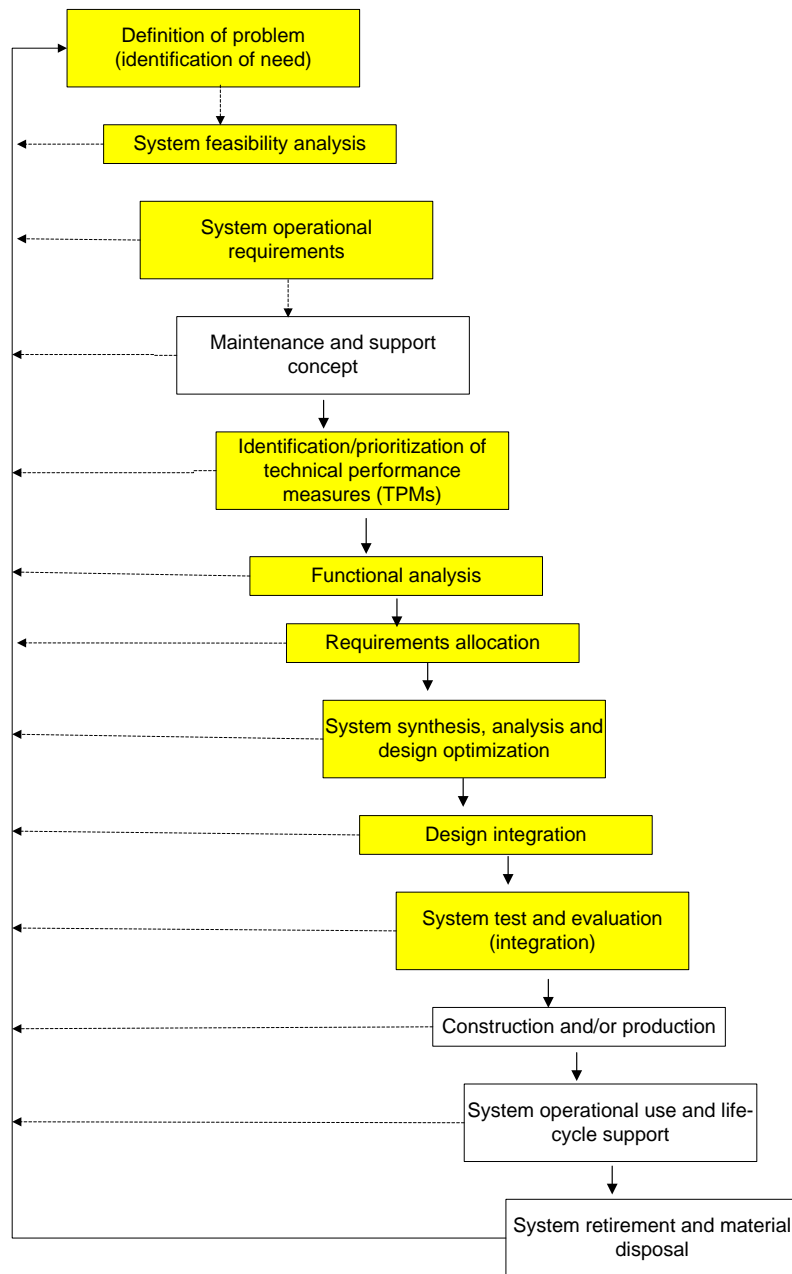


Figure 9 - System Design and Development Process (Blanchard, 2008)

Although the process is more directed to the early stages of system design and development, consideration for the activities in the latter phases of production/ construction, operational utilization, and system maintenance and support is essential in



an effort to understand the consequences of prior decisions, and the establishment of guidelines and benchmarks for the future. These activities represent a process that should be applied each time there is a newly identified requirement for a system. The steps provided in Figure 9 must be tailored to both system and process requirements. The shaded/colored steps were considered suitable for the purpose of this work and followed, either completely or partially, in the system development. Often there are many iterations that occur, not only within the process overall, but within each of the blocks.

In Brown (2009) , a new way of looking at the design as a whole is proposed. The author provides an explanation of how the techniques and strategies for the design are linked at every level of business. Brown introduces design thinking as the collaborative process by which the designer's sensibilities and methods are employed for matching the needs of people relative to what is technically feasible and viable as a business strategy. In short, design-thinking converts need into demand. It is a human centered approach to problem solving that helps people and organizations become more innovative and creative. Design thinking is not just applicable to so-called creative industries or people who work in the design field. According to the author, the approach has been used by organizations such as Kaiser Permanente to increase the quality of patient care by re-examining the ways that their nurses manage shift change, or Kraft for rethinking their supply chain management.

According to (Kossiakoff, Sweet, Seymour, & Biemer, 2011), there are many ways in which to define systems engineering. The authors define the term in a very concise yet meaningful way: The function of systems engineering is to guide the

engineering of complex systems. They further define the key words in the definition as follows:

- To guide – to lead, manage or direct; usually based on a superior experience in pursuing a given course and to provide a preferred course of action
- Engineering – the application of scientific principles to practical ends; as the design, construction and operation of efficient and economical structures, equipment and systems
- System – a set of interrelated components working together towards some common objective
- Complex – restricts the definition of systems in which the elements are diverse and have intricate relationships to each other

For the purpose of this research, Systems Engineering was divided in two major components (System Modeling and System Design) in order to differentiate between the design and modeling sides of the work. Both components are further split into sub-components (Systems Dynamics, Equations and Standards on one side, and QFD and Pugh Matrix on the other).

#### 2.1.1.2. Pugh Matrix

In Burg, Hill, Brown, & Geiselhart (1997), the authors demonstrate an application of advanced design methods, involving Multi-Attribute Decision Making. The technologies were qualitatively assessed using a Pugh Evaluation Matrix, which helped estimate the effects of each technology on the overall system and their impact on design requirements. The design requirements included performance metrics, reliability, safety and noise. Expert opinions from selected individuals in various industries, academia and

government organizations were solicited to ensure a thorough understanding of the technology impacts and subsystem interaction. First, they were asked to estimate the relative customer importance of each design requirement in the Pugh Evaluation Matrix by choosing a weight value between 1 and 10, with 10 representing the most significant criterion. When these expert opinions differed, an average value or a value judged as the most appropriate was chosen based on the reasoning behind the various opinions. Subsequently, they were asked to judge if a technology had positive, negative or no impact on each evaluation criteria relative to the baseline, and to determine if the effect was strong, medium, normal or weak in magnitude. The qualitative judgments were subsequently mapped to numeric values (1, 4, 7, 9, 10, 11, 13, 16, and 19), with 10 representing the baseline value.

In the same paper, a Morphological Matrix, which is also used and introduced in Chapter 3.3, was used to functionally decompose the entire aircraft system into subsystems, and to brainstorm on the technologies applicable to each subsystem. A qualitative technology assessment was performed using a Pugh Evaluation Matrix that focused on what effect a certain technology had on both the overall noise level of a particular subsystem. The authors have a more analytical approach in not only calculating the weights but also comparing the distance of each individual configuration from an ideal result. Although the design tools were not applied in a healthcare environment, similarly to this work, they were employed in the development of a complex system rather than a product.

In (Verma, Smith, & Fabrycky, 1999), the authors conclude that a disciplined design process is essential for effective and efficient development of systems which are

both responsive to customer needs and globally competitive. This paper presented a methodology for the systematic analysis, evaluation and selection of a design concept. Application of concepts from fuzzy set theory facilitates comprehensive and enhanced richness in the design specific information captured and conveyed to the design team. The paper represents an extension of ongoing research in the application of fuzzy set methods to evaluate design concepts. Since lack of precision and vagueness characterize this nascent design phase, the QFD method and the Pugh concept selection process are modified and extended with concepts from fuzzy set theory. The approach used by the authors can be an essential supporting factor in a healthcare prevention system design due to a continuously increased complexity of the system. While the traditional function of the design concepts (e.g., QFD, Pugh and Morphological Matrixes, etc.) are immediately applicable to product and process design, as well as in smaller systems development, for complex systems such as the one proposed by this work, needed new and innovative ways for adapting the traditional concepts to the new environment.

The work presented in this paper suggests utilizing different approaches but in a similar fashion to what was attempted by (Verma, Smith, & Fabrycky, 1999) for offering solutions to complex system design challenges. One method is to use a unique system VoC that eliminates the need for multiple QFDs. The approach is explained in greater detail within the subsequent chapters.

According to (Suh, 2001), engineering activities consist basically of synthesis and analysis, which mutually reinforce each other in a feedback loop. Rational synthesis makes analysis simple, whereas rigorous analysis of a synthesized engineering system provides the means for improving the system through a fundamental understanding.

Design which is fundamental to engineering encompasses both synthesis and analysis. Both, “engineering science for analysis” and “engineering science for synthesis” are critically needed in design.

In (Harvey, 2007), the author describes several tools used in system design, as well as applies them in a fictitious service providing company. When several options for system design are developed, the Pugh Matrix is used for converging to the best possible solution. Accordingly, a Pugh Matrix is the tool of choice to perform a systematic comparison of concepts against a weighted set of criteria, therefore it is used in this work. The author underscores the fact that several iterations are usually required in order to converge and develop the best solution. A description of the iteration process is also offered in the paper where it transitions from the initial concept or even the benchmarked solution to the final design.

The approach proposed by this work provides additional leverage for convergence in complex systems. The Pugh Matrix is introduced at the sub-system level to synthesize the possible design solutions. Additionally by initiating the system design process from a higher level (i.e., identify and capture the SYSTEM VoC before attempting to design its subsystems), the most difficult step for the convergence of the proposed system solutions is automatically addressed. In other words, all the sub-systems of the healthcare prevention system emerge directly from it. Consequently, the convergence is “forced” at the lower levels which is easier to address in general. This means that in the potential obesity sub-system solutions, it is preferred to attempt converging the solutions at the healthcare prevention system level, though it is typically not easy to find convergence.

A very thorough analysis and comparisons against other methods are presented in (Frey, Herder, Wijnia, Subrahmanian, Katsikopoulos, & Clausing, 2009). This is one of the more recent contributions to the area of system design methods and tools. There are several relevant conclusions made by the authors as follows:

(1) In practice, the datum concept is significantly stronger than the rest of the population. Since the datum is not arbitrary, it seems less problematic that datum selection can influence the process, for example by slowing convergence. In this work, the datum was based on what was perceived being the current solution in the area of interest. More detailed explanations are provided in a later chapter when the Pugh Matrix was used in synthesizing the design concepts.

(2) If there is a strong datum concept, the first round of iterations reduces the set of alternatives by a substantial degree, ranging from 25 to 70% in most cases.

(3) If the datum is not strong in some particular case, even though Pugh's approach is properly followed, the consequence would not necessarily be a poor decision, but rather lack convergence in the first round. The process as modeled in the paper, tends to retain many concepts rather than risk eliminating anything worthwhile.

(4) A single run of the Pugh matrix rarely leads to selection of a single alternative. This is to be expected since the matrix is part of an iterative process of learning and creative synthesis.

In the design of a feasible healthcare prevention system, the identification of the best solution may be challenging due to its complexity and multitude of stakeholders that need to be considered. To clarify, due to possible conflicts between different customer groups with their own needs, convergence towards the best alternative can be difficult.

By using the Pugh Matrix at the system design level and following the suggested points from the authors, a robust, cost effective and feasible solution can be developed.

The authors conclude that the models presented support the contention that Pugh Controlled Convergence is an effective method to apply during the concept design phase. They also support the notion that Pugh's method encourages greater objectivity in engineering decision-making.

#### 2.1.2. System Modeling

The System Modeling branch in Figure 8 also consists of two major components: Systems Dynamics and Equations & Standards.

##### 2.1.2.1. System Dynamics

In the introduction by (Senge, 1990), the author claims that for many situations, significant progress in systems thinking seems to be harder to achieve than progress in other disciplines. According to the author, part of the problem is motivation so areas such as working with mental models, dialogue and shared vision have a strong appeal. The author describes three critical points in the development of systems thinking that can easily be extrapolated to the way people react towards the systems around them, particularly related to the obesity pandemic but also applicable in other healthcare issues. A similar approach is considered within the work being presented. These three critical points can be described as follows:

- Structure Influences Behavior – Different people in the same structure tend to produce qualitatively similar results. When there are problems, it is easy to find someone or something to blame. More often than we realize, systems create

their own crises, and not by external causes or mistakes by individuals. This might also be considered as an important element in the way people deal with their obesity condition, taking into account the more external environment rather than the internal control system.

- Structure in Human Systems is Subtle – We tend to think of “structure” as external constraints on the individual. Structure in complex living systems such as the “structure” for multiple “systems” in the human body, can be described as the basic interrelationships that control behavior. The obesity problem is quite complicated since it emerges from the intricacies of the human body.
- Leverage Often Comes from New Ways of Thinking – In human systems, people often have potential leverage that they do not exercise because they focus only on their own decision, and ignore how their decisions affect others.

The systems perspective demonstrates that there are multiple levels of explanation in any complex situation. The three levels are: Systemic Structure (generative), Patterns of Behavior (responsive) and Events (Reactive).

(Sterman, 2000) provides details for one of the pillars of system modeling and, system thinking, in general. The author believes that effective decision making and learning in a world of growing dynamic complexity requires us to become system thinkers – to expand the boundaries of our mental models and develop tools for understanding how the structure of complex systems creates their behaviour. The book introduces the reader to system dynamics modeling for the analysis of policy and strategy, with a focus on business and public policy applications. System dynamics is also a rigorous modeling method that enables the construction of formal computer



simulations of complex systems, where the simulations can be used to design more effective policies and organizations. Sterman first explains how accelerating the economic, technological, social and environmental change challenges managers and policy makers to learn at increasing rates, while the complexity of the systems in which we live is simultaneously growing.

System dynamics is a perspective and a set of conceptual tools that enables users to understand the structure and dynamics of complex systems. While being concerned about the behaviour of complex systems, system dynamics is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics and engineering. These tools are applicable to the behaviour of humans, as well as physical and technical systems, system dynamics draws on cognitive and social psychology, economics, and other social sciences.

In (Flatt J. , 2004), the author uses System Dynamics (SD) to model elements related to obesity. The author introduced a SD computer model, developed to examine how the interactions between carbohydrate and fat metabolism influence body weight regulation. In this work, it is recognized that the metabolism of living organisms and its regulation are exceedingly complex, reflecting the outcome of a biological evolution that enables humans and animals to function and sustain themselves under a multitude of conditions. The author uses SD modeling with a two-reservoir system, representing the body's limited glycogen and large fat reserves. The outflows from the reservoirs correspond to the oxidation of glucose and fat, for which their relative contributions are affected by the size of the prevailing glycogen and fat reserves.

(Homer & Hirsch, 2006) provide strong statements by stating that the systems modeling methodology of system dynamics is well suited to address the dynamic complexity characterizing many public health issues. Users of system dynamics modeling for chronic disease prevention should seek to incorporate all the basic elements of a modern ecological approach, including disease outcomes, health and risk behaviors, environmental factors, and health related resources and delivery systems. System dynamics exhibits promise as a means of modeling multiple interacting diseases and risks, interaction of delivery systems and diseased populations, and matters of national and state policy.

The authors also explicitly describe obesity as one of the direct applications of SD. As long as there are dynamically complex health issues that require answers, the SD approach will have a place in the analytic library. It has already been utilized for making significant contributions in addressing epidemiological issues, as well as issues of health care capacity and delivery, and patient flow management.

There is still much to be learned about the population dynamics of individual chronic conditions such as hypertension and risk factors like obesity. SD models can also address multiple interacting diseases and risks, giving a more realistic picture of their overall epidemiology and policy implications, particularly where the diseases and risks are mutually reinforcing.

In (Brailsford, 2008), the author discusses some of the possible reasons for the growth in popularity of SD within healthcare modeling. According to the author, SD has traditionally been used at a higher, more aggregated and strategic level than Discrete

Event Simulation (DES). SD models can be highly complex but they exhibit dynamic complexity rather than detailed complexity.

The author claims there are a number of reasons why SD is particularly well suited to healthcare problems, where this may justify the explosion in new applications using the approach. It is rare in a healthcare setting for a stakeholder to draw well defined boundaries around the system of interest, and ignore any interactions with the surrounding environment. For many healthcare problems, there are multiple stakeholders with conflicting objectives, and different levels of ownership and power within the system as a whole. The qualitative aspects of SD are very helpful when trying to understand such issues.

Data availability and quality is another issue. Any DES model requires a substantial amount of detailed data for developing fit distributions. On the other hand, the data requirements of SD are typically much less, since SD models are usually higher level and more aggregated. In a DES model, users often cannot see the higher level concerns since they are so obsessed with the detail and lose sight of the bigger picture. In SD, the detail cannot be modeled, but an understanding of the dynamic complexity of the system can be gained. SD models are not dependent on vast quantities of high-quality data, and so they can be used at a more speculative or strategic level, for larger populations and longer time-horizons. A key advantage of SD is that the models generally process data very rapidly (and of course do not require multiple iterations), so they can be operated interactively in real time with decision-makers.

(Meadows, 2008) introduces systems thinking in a concise way and offers insight in problem solving on scales ranging from the personal to global. As the author mentions,

once the relationship between structure and behavior is observed, the stakeholder can begin to understand how systems work, what makes them produce poor results, and how to shift them into better behavior patterns. As the world continues to change rapidly and become more complex, systems thinking helps stakeholders to manage adapt and see the wide range of choices available. It is a systems way of thinking that provides the freedom to identify root causes of problems and recognize new opportunities.

In (Surhone, Tennoe, & Henssonow, 2010), the authors have assembled the essential concepts from the SD field while using Vensim as the simulation software. While the fundamental concepts are preserved, an array of dynamic functions and routines are embedded in the software that allow the user to simulate the dynamic behavior of various systems. There are options that also support the user in presenting and interpreting the data.

According to the authors, three elements of the SD method differentiate it from other modeling methods, as described below:

- SD explains why a system changes overtime, as opposed to why a systems is in a particular state at any point in time
- SD takes a broad view of the factors that cause changes, as opposed to a more detailed microscopic view
- SD illustrates reciprocal feedback relationships between variables, instead of simple one-way causality, similar to most statistical methods

The choice for Vensim as the preferred environment compared to other similar offerings for simulation was based on a few characteristics. In Table 2, the most influential software providers for SD modeling are listed with links to the respective

company websites. As a general note, there are very few companies that have developed SD software. In addition to the companies listed on Table 2, there are several that are web-based. Those were not included on the list.

Table 2 – Major Software Packages for SD Modeling

#	Package name	Free?	License type	Last updated (year)	Contact	More info
1	Vensim	Y	Commercial	2010	<a href="http://www.vensim.com/">www.vensim.com/</a>	PLE version free for educational and personal use; non-free versions for commercial use
2	AnyLogic	N	Commercial	2010	<a href="http://www.anylogic.com">www.anylogic.com</a>	supports system dynamics, agent based and discrete event modeling
3	Stella, iThink	N	Commercial	2009	<a href="http://www.iseesystems.com/">www.iseesystems.com/</a>	
4	Consideo	N	Commercial	2010	<a href="http://www.consideo-modeler.de/">www.consideo-modeler.de/</a>	(commercial software combining different methods, concept maps, system dynamics)
5	TRUE	Y	Trial 30 days (unlimited for educational) & commercial	2011	<a href="http://www.true-world.com">www.true-world.com</a>	System dynamics + 3D Modeler (3D Rendering using OpenGL graphics library) + Procedural animation
6	Simile	N	Commercial	2011	<a href="http://www.simulistics.com/">www.simulistics.com/</a>	non-free System Dynamics software with object-based concepts
7	Powersim	N	Commercial	2011	<a href="http://www.powersim.com">www.powersim.com</a>	Supports system dynamics and discrete event modeling

The choice for Vensim was made based on researching for desired features and characteristics. Some of the vital characteristics that make Vensim suitable for the purpose of this research are listed below:

- Language used is the same as the key SD manuscript entitled “Business Dynamics” by (Sterman, 2000)
- Free version of Vensim PLE is available for learning purposes
- Forum available for posting questions
- Fully supports the SD method
- Allows flexible graphical representations without clutter
- Contains an assortment of user-friendly tools for model analysis and testing

- Instantaneous visualization of results with SyntheSim
- Extensive data use and calibration capabilities
- Rich array syntax
- Open architecture
- Optimization algorithm
- Extensive treatment of data, with many flexible import/export options

Another important selection consideration used when choosing Vensim was the fact that other researchers in the IMSE department at University of Windsor were already using the software.

#### 2.1.2.2. Causal Relationships and Standards

A detailed listing of the causal relationships related to obesity will be further presented in a later chapter.

In (Schulz & Schoeller, 1994), the authors claim that the number of physical activity measures and indexes already referenced in the literature is quite large, and may result in some difficulty for the average investigator to choose the most appropriate measure. Accordingly, the paper provides information on the utility and limitations of the various measures. Its primary focus is the objective assessment of free-living physical activity in humans based on physiological and biomechanical methods.

In (Christiansen, Garby, & Sørensen, 2004), the authors claim that obesity is typically developed over a long time and this is reflected in an energy imbalance, which is too small to be measured and controlled. Their objective was to formulate a mathematical model for the relationship between the change in Body Mass, and the

values of the Energy Intake (EI) and Energy Expenditure (EE), controlled by the Physical Activity Factor (PAF). The inclusion of increased energy expenditure to convert food energy to tissue leads to modifications in the previous estimates for energy imbalance by approximately 20%. Accordingly, the authors developed a differential equation that quantifies another component of the change in body mass ( $\text{dBM}/\text{dt}$ ) as a function of EI, PAF, BM and several constants.

Through their work, the authors address the following questions:

- If a person in steady state (i.e., when EI equals EE) instantaneously changes EI and/or physical activity level and keeps the new values constant, what is the resulting change in the steady-state body weight?
- In the same situation, what is the rate of weight change?
- Assuming a constant increased rate in body weight, for example 1 kg/year, by how much does the energy intake exceed the energy intake in steady state?
- Can the theory predict the result of difficult observations in humans that require long observation periods?

In (Gerrtor, Juan, & Basiotis, 2006), the authors argue that the Dietary Reference Intakes (DRIs) define the daily requirement for energy as the Estimated Energy Requirement (EER). The EER is based on calculations that account for an individual's energy intake, energy expenditure, age, sex, weight, height and physical activity level.

Including the physical activity level in the calculations subsequently allows for the energy expenditure to be determined and achieving energy balance as a more realistic goal. However, physical activity level is often difficult to measure and accurate assessment of energy expenditure is not always possible. The authors provide a simplistic

method to calculate daily EERs for adults based on physical activity level. They use the EER causal relationships of the DRI Committee and provide a spreadsheet template for the calculation of physical activity level. This technique accounts for all factors and measurements to determine the physical activity level and energy expended from the daily physical activity.

(Butte, Christiansen, & Sørensen, 2007) developed a model based on empirical data and human energetics (branch of mechanics that deals primarily with energy and its transformations, according to Merriam-Webster dictionary) to predict the total energy cost of weight gain, and obligatory increase in the energy intake and/or decrease in physical activity level, associated with weight gain in children and adolescents. The authors capture the main three components responsible for the energy balance (PAF, Basal Metabolic Rate (BMR) and EI), where  $(dBM/dt) = f(\text{PAF}, \text{BMR}, \text{EI})$ .

The authors conclude that the development of childhood obesity most likely occurs from a combination of surfeit (intemperate or immoderate indulgence in something such as food or drink) of EI and a decline in physical activity. However, the plasticity of dietary intake is greater than that of physical activity, meaning it has a greater influence. Given the mandatory physical activities required for daily living, weight gain in sedentary children and adolescents whose Physical Activity Levels (PAL) are at the physiological minimum is attributable to excess dietary EI.

The objective of the (Lazzer, et al., 2009) study was to explore the relationship between basal metabolic rate (BMR), gender, age, anthropometric characteristics, and body composition in severely obese caucasian subjects. BMR can be considered as the sum of the Energy Expenditures (EEs) of tissues and organs in a fasting and resting state,



and in thermoneutral conditions. It depends on the mass and metabolic rate of tissues and organs. Generally, BMR depends on body composition as expressed by fat-free mass (FFM), fat mass (FM), gender, age, physical activity, and nutritional status. The main determinant of BMR is FFM, whereas FM is significant only in obese subjects. Gender is also a significant determinant of BMR, with men having a greater BMR than females after adjustment for body composition. In addition, BMR markedly decreases with advancing age in sedentary populations at a rate of approximately 1 to 2% per decade after the age of 20. Such a decline in EE probably contributes to an impaired ability to regulate energy balance with age.

## 2.2. Evidence Based Theory

(Davidoff, Haynes, Sackett, & Savage, 1995) claim doctors need to know about the studies describing the successes of new ideas, but the volumes of such literature has grown enormously. Other hindering points include the fact that many publications are inaccessible, remain unpublished, or have serious flaws. Most doctors lack the time or skill to track down and evaluate the published evidence. Although the skills of searching for evidence and critically appraising it are being mastered by a growing number of doctors, many cannot maintain the pace of technology. As an example, only in a single technology field represented by the blood pressure monitoring devices, according to (Bacoiu & Pasek, 2012) more than one thousand patents were issued in the past 100+ years, with the vast majority of those issued in the last 30-40 years. Consequently, there is a widening gap between what ought to be done in comparison to what is actually accomplished. A similar way of thinking is documented in (Pfeffer, 2000), where an

attempt is made to find the answer for “Why so many managers know so much about organizational performance, say so many smart things about how to achieve performance, and work so hard, yet are trapped in firms that do so many things they know will undermine performance”. In the author’s case, knowing was not enough, and there was a gap between knowing and applying the knowledge when and where it was needed.

Evidence based medicine relies heavily on statistical analysis and quantitative methods and attempts to fill the void by helping doctors find the information that ensure they can provide optimum management for their patients. In essence, evidence based medicine is rooted in five linked ideas, in the following order:

- Clinical decisions should be based on the best available scientific evidence
- Clinical problem - rather than habits or protocols - should determine the type of evidence to be sought
- Identifying the best evidence means using epidemiological and biostatistical ways of thinking
- Conclusions derived from identifying and critically appraising evidence are useful only if put into action when managing patients or making health care decisions
- Performance should be constantly evaluated

According to the author, the practice of evidence-based medicine seems to halt the progressive deterioration in clinical performance that is otherwise routine, and which continuing medical education cannot stop.

In (Munro, 2005), the author updated the examples from the literature and included additional content primarily in the area of preparing data for statistical analysis.

She focuses on the most current and frequently used statistical methods in today's healthcare literature, covering essential material for a variety of program levels including in-depth courses beyond the basic statistics curriculum.

(DiCenso A. G., 2005) introduced a relatively new term in healthcare entitled "Evidence-Based Nursing" (EBN). The book adds important aspects to the term referred to in this dissertation as "Evidence Based 'X'" (EB'X'). EBN is defined as an integration of the best evidence available, nursing expertise, and values and preferences of the individuals, families and communities who are served. This approach to nursing care bridges the gap between the best evidence available and the most appropriate nursing care for individuals, groups and populations with varied needs.

Although the book is intended for the nursing profession, where the examples are mostly from healthcare, the concepts are very much common to all the other EB'X's. In fact, it is the researcher's belief that Evidence Based concepts can be easily reduced to a core theory from where all other "customization" for different fields can be readily performed by bringing specifics to the common core.

The authors of (Ko & Tang, 2007) use evidence-based research to propose a change in the assessment of obesity in a certain category of people that can eventually be applied to others. According to their research in recent years, central obesity (fat tissue around the waist) with increased intra-abdominal adiposity has been confirmed to be one of the most important cardiovascular disease (CVD) risk factors. The health risk associated with central obesity has been reported to be even more prominent than general obesity, as measured by Body Mass Index (BMI).

In (Kropski, Keckley, & Jensen, 2008), the authors note both the scarcity of studies involving school programs for addressing obesity at a very early age and the importance of the education as a critical factor. The authors explain that our ability to draw strong conclusions on to the efficacy of school-based obesity prevention programs is limited by the small number of published studies and various methodological concerns. Qualitative analysis suggests programs grounded in social learning may be more appropriate for females, while structural and environmental interventions enabling physical activity may be more effective for males. High-quality evaluation protocols should be considered essential components in future programs.

In (Khoury, Feero, & Valdez, 2010), the authors present an examination of how the evidence-based medicine (EBM) paradigm intersects with Family History (FH) and Personal Genomics (PG), where these are the two areas that are at the core of personalized medicine.

Evidence-based medicine has its roots in assessing the benefits-versus-harms trade-off resulting from actions such as screening, diagnostic tests, and therapeutic and preventive interventions. For any clinical or public health action, practitioners of EBM try to evaluate whether or not the benefits of such action reasonably exceed the harms. An inherent perceived tension in the EBM approach to healthcare and disease prevention arises from the fact that recommendations for individuals are made based on “average” information derived from population-level data. This approach, though effective across the population as a whole, may not always be perceived as serving the interest of individuals with specific disease characteristics, genetic factors, risk factor information, and personal preferences.

FH and PG may well become fundamental infrastructure tools for health and healthcare in this century. This approach would transcend the usual EBM paradigm of evaluating “applications” one at a time. Both tools have the potential to improve the way EBM recommendations are developed and applied to health care and disease prevention.

### 2.3. Healthcare Prevention

In Figure 8, there are the two elements for the Healthcare Prevention subsystem which include: Policy Development, Obesity Management and Psychology.

#### 2.3.1. Policy & Obesity Management

What is “prevention”? The authors of (Coohey & Marsh, 1995) conducted a content analysis for prevention definitions in the general prevention literature. The pros and cons of the traditional trilogy (primary, secondary and tertiary) for prevention definitions are examined, along with a description of key concepts, such as end-states, timing, targets and eligibility criteria. The authors propose a conceptual alternative to this prevention trilogy, in favour of one that distinguishes among prevention, treatment and rehabilitation. They argue that a prevention science must generate a body of knowledge that explains how a desirable or undesirable end-state develops. This is accomplished by identifying the individual and environmental factors that increase the probability for a specified desirable or undesirable end-state occurring.

(Kasser & Ryan, 2001) in the context of obesity and healthy lifestyles, argue that people are rarely provided incentives or rewarded for making healthful lifestyle choices, whether the choices concern food or physical activity. The rewards currently must come

from within the individual, and these rewards alone have not been successful in motivating large segments of the population to change their health behaviours.

A very interesting point is described in (Peters, 2003). There is a growing consensus among experts that the trend in obesity sweeping the nation is not caused by defective biology but rather is environmentally driven. In fact, obesity may be viewed as a normal biological adaptation to the prevailing environment, rather than a physiological system gone awry. For many people, weight gain is the only means to achieve energy balance in an environment that encourages excess energy intake and very low levels of physical activity.

Among many other very valid points that the author makes, one was considered by the researcher of critical importance. The question is, “What changes will be necessary to have a meaningful impact on obesity in the next several decades?” In this issue of Obesity Research, (Baranowski, Cullen, Nicklas, Thompson, & Baranowski, 2003) point out that current behavioural change models have not been very successful at changing long-term eating and physical activity patterns, and may be inadequate to support successful interventions for reversing the obesity epidemic.

In a comprehensive report by (Lassard, 2006), the authors explain that the solution to promoting healthy weights is often presented as an easy one which includes eating right and exercising. This simple solution appears to resonate strongly with the Canadian public, as indicated by a recent Canadian Population Health Initiative (CPHI) funded public opinion telephone survey. Policy-making can be influenced by a number of factors, including evidence-based research, political will and availability of resources. It can also be influenced by public opinion. As outlined in the report at a population level,

addressing this complex health issue is anything but simple, and can involve individual behaviours, as well as environmental and social factors. While eating and physical activity have a direct impact on body weight, both can be influenced by the settings in which we live, learn, work and play, including: community and physical environment, workplace, school, home and family environment, nutrition environment, and personal health services.

Why have people been largely unsuccessful? It might be argued that people have attempted to change eating and physical activity patterns, behaviours (Zelick, 2007) (Winkel & Petermann, 2007) that are motivated by multiple drivers not necessarily related to health, through mediators that are not of primary importance to the individual at the point of decision, given the totality of immediate personal priorities and rewards facing the individual.

(Levine & Koepp, 2011) argue that one very important aspect is not overseen, and includes the responsibility of the general population and accountability related to the fight against obesity. The Patient Protection and Affordable Care Act (P.L.111-148) may be an important solution bridge to help end obesity in the United States. Although The Act impacts multiple aspects of an obese patient's health, it is not entirely a one-way street. For example, failing to have health insurance will result in a person being fined. The Act may also provide employers an opportunity to financially penalize overweight workers by adjusting cost sharing in employer-sponsored health insurance. In addition, The Act opens the door towards punitive measures for high-risk health behaviours.

### 2.3.2. Psychology

In (Cohen, Kamarck, & Mermelstein, 1983), the authors present evidence for the reliability and validity of a 14-item instrument entitled the “Perceived Stress Scale” (PSS). It is designed to measure the degree for which situations in one’s life are appraised as stressful. It is a common assumption among health researchers that the impact of “objectively” stressful events is, to some degree, determined by one’s perceptions of their stressfulness.

There are some clear advantages to objective measures of stressful events. First, such measures permit an estimate of the increased risk for disease associated with the occurrence of easily identifiable events. Second, the measurement procedure is often simple (e.g., did this event occur during the last six months), and in many cases, persons experiencing a particular event can be identified without the necessity of asking them about the occurrence of the event (e.g., persons living in noise impacted communities). Third, these measurement techniques minimize the chance of various subjective biases in the perception and reporting of events.

In (Mullan, Markland, & Ingledew, 1997), a Behavioral Regulation in Exercise Questionnaire (BREQ) was developed to measure external, introjected, identified, intrinsic and amotivated forms of regulation for exercise behavior. The BREQ may allow finer analysis of the motivational forces at play in exercise adoption and maintenance situations. A focus on underlying, source level motives for exercise, as represented by the behavioral regulation continuum, rather than surface level motives (such as weight control, socialization and fitness), may increase the understanding of the way in which perceived self-determination for action influences behavior. Knowing a person's surface



level motive for undertaking a behavior, may not pin point their regulatory source. For example, exercise for purposes of weight control could be regulated by the importance and value of a trim body, guilt at failure to expend more calories, or control medical conditions. Therefore, it may be unwise to gauge the degree of self-determination from such specific motives. Furthermore, the BREQ's implied continuum and its theoretical background, which considers the development of internal regulation of initially non-intrinsically interesting behaviors, makes it ideally suited to examining motivational change across a period of behavior change such as exercise adoption.

In his article (Sheldon, 2001), the author attempts to answer the question, “How do people go about selecting life-goals for themselves, and how can this process go awry?” The author presents and discusses the implication of the self-concordance model of goal striving. The model focuses on the personal goals that individuals generate for themselves, and the sense of ownership that people feel (or do not feel) for those goals. As Sheldon argues, people sometimes fail to create goals that correctly represent their true or actual needs, values and interests. As a result, they may fail to attain those goals, or fail to benefit emotionally, even if they manage to attain them.

(Dishman, 2008) introduces a model of personal, social environmental and physical environmental influences on personal choice to be physically active, as illustrated in Figure 10.

In (Rutters, Nieuwenhuizen, Lemmens, Born, & Westerterp-Plantenga, 2008), the authors explain that obesity results from chronic deregulation of energy balance, which may in part be caused by stress. Their objective was to investigate the effect of acute and psychological stress on food intake. They found that acute psychological stress, indicated

as an increase in state anxiety and Profile of Mood State (POMS) scores, was related to an increase in energy intake during the absence of hunger in adults. Moreover, subject-specific features including higher trait anxiety scores were related to a larger increase in state anxiety scores during the stress condition.

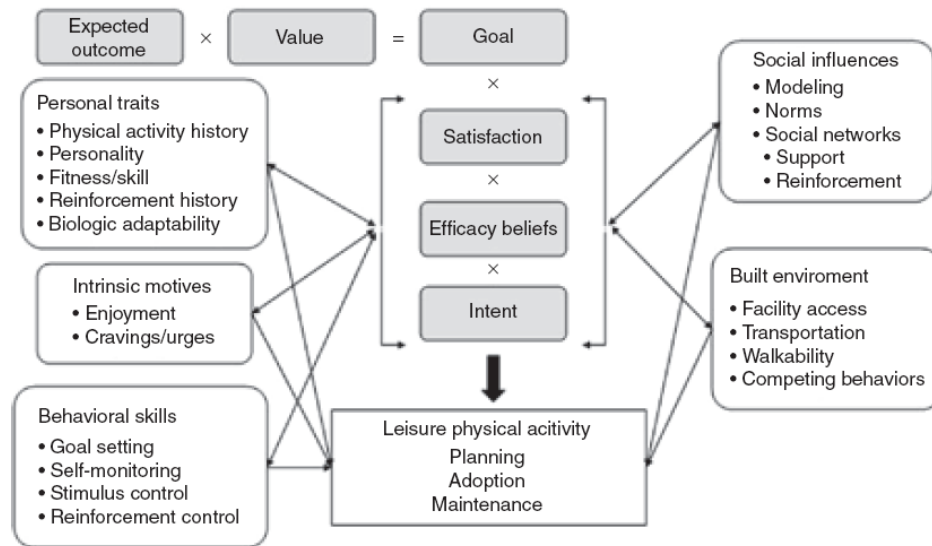


Figure 10 - Social-Cognitive Influences on Personal Choice

(Taubes, 2011) has a very different way of evaluating the obesity problem. He argues that physicians previously were not thoughtless, nor are the present day doctors. They merely have a flawed belief system or a paradigm which stipulates the reason individuals become obese is clear and not convertible, as is the cure. Physicians tell their patients they become fat because of eating too much and move too little, where the cure is to do the opposite. This way of thinking about personal weight is so compelling and pervasive that it is virtually impossible nowadays not to believe it. Even if there is an abundance of evidence to the contrary – no matter how much time in their lives patients spend consciously trying to eat less and exercise more without success – it is more likely

that an individual will question their own judgment and willpower than the notion that their adiposity is determined by the number of calories consumed and expended.

#### 2.4 Literature Review – Concluding Comments

The challenging part of the Literature Review process was not in identifying research papers supporting the major components of this work. That is because there are rather rich research sources in the fields of System Engineering, Healthcare Prevention as well as Evidence Based Theories. The challenge was in identifying research in one of the fields that directly addresses issues in the other ones.

For example, there is considerable meaningful research in QFD as well as its application to product design and process design level in industrial applications. However, there is less research applying the methodology at the system level, particularly in healthcare. Also, within the obesity section, there are sources of reliable, academic research in the field of physical behaviour of the human body. However, it is less research available in the area of the psychological factors influencing the obesity pandemic.

Overall, the previous research identified throughout the Literature Review supports the methodology proposed by this work. The progress made in system design in the direction of broadening the understanding and usage of the concepts together with the progress made in system thinking allowed for the application of the concepts in a unique, multidisciplinary approach for the development of the AMHSC.

## CHAPTER III

### SYSTEM DESIGN METHODOLOGY

#### 3.1. The Proposed System Design Methodology

In (Brown T. , 2009) a new way of looking at design as a whole is proposed. Following the same holistic perspective, this research proposes a methodology for developing systems in healthcare by considering simultaneously the system as well as the subsystems in one unified approach.

While the design methods are used in various fields as pillars for development of new product and processes, they are, in general, rarely used for system design and analysis in healthcare. (Dijkstra & van der Bij, 2002) also suggested that there is very little experience with the application of these tools particularly in healthcare and other service sectors in general. Some of the challenges recognized by the authors involve the difficulty for clearly, and/or uniquely answering the two key questions of: “Who is the customer?” and “What exactly is the product?”.

This research adapts system design concepts for the purpose of AMHSC development and in support for the transition from a macro-system to subsystems. Particularly the latter part (i.e. the transition system to subsystems) is one of the novelties of this research that can be used in various other applications.

Systems engineering processes are inherent within and throughout the overall system life cycle (Blanchard, 2008), with the emphasis on a top-down, integrated, life-cycle approach to system design and development. This research follows a similar approach by integrating the system / subsystem development.

As pictured in Figure 11, the whole process is initiated by understanding the system needs from the stakeholders' perspective, followed by definitions of metrics, assessment of technology and feasibility analysis.

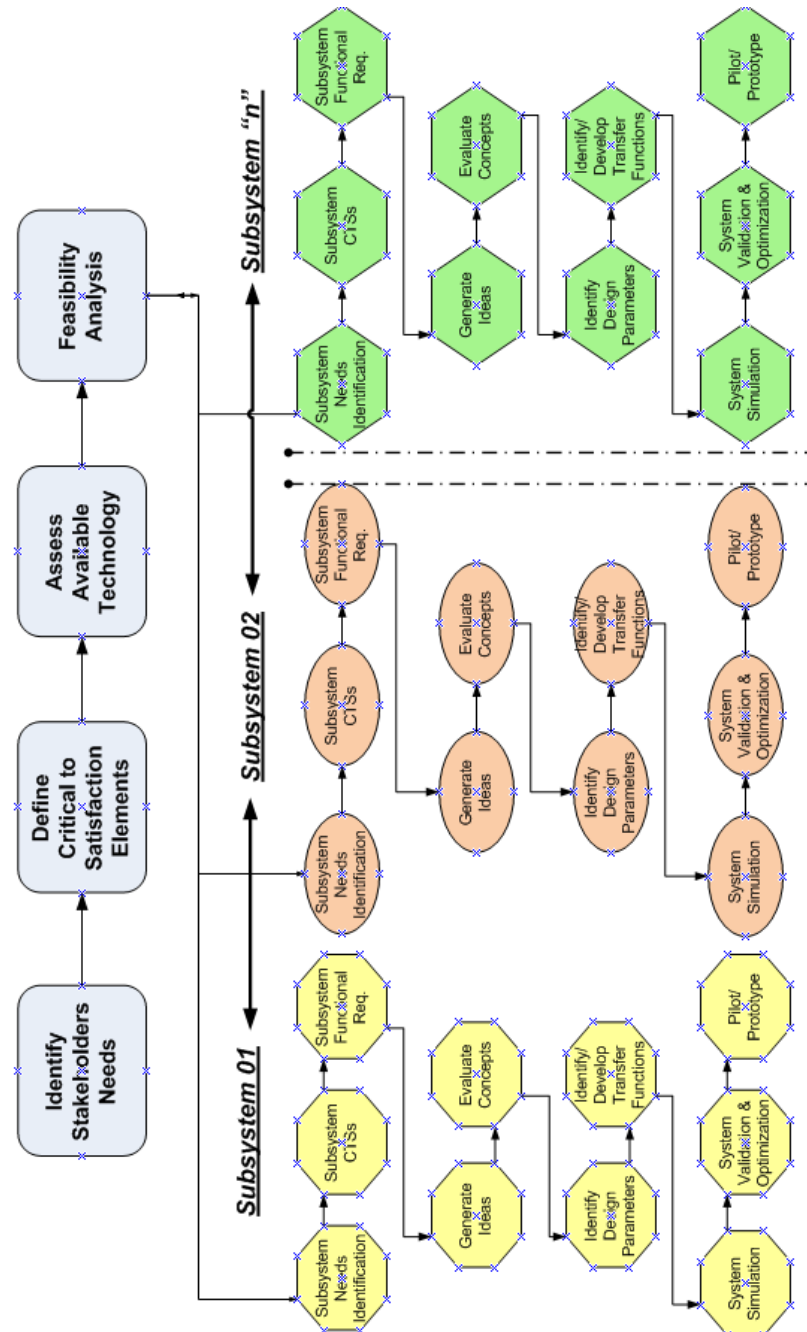


Figure 11 – Subsystem to System Transition Methodology

The upper side of the chart shows key steps in the system development stage. Before attempting to develop the actual final subsystem, the higher system is designed to the level beyond only understanding the Voice of the Customer (VoC). That is, after identifying the needs of the stakeholders, the resulting Critical to Satisfaction (CTS) elements are recognized. CTSs are identified measures of the VoC. That is, what measures we need in place in order to quantify each of the elements that make VoC. An early understanding of the technology available as well as the possible gaps can then be brought into the discussion. The gap could be either a complete lack of technological means to fulfill certain needs identified by the customer or, alternately, an existing technology that can only partially support the VoC and needs to be developed further. Deciding whether or not the system is feasible at such a high level of development is the last step before integrating the subsystems.

Within the lower portion of the chart in Figure 11 are the subsystems that are part and together form the higher level system. In the example used as part of this research, a subsystem is built similarly as Subsystem 01 on the chart. However, one of the challenges faced in building such a subsystem is the need to develop a direct link between the higher level and a secondary level. Considering a two-dimensional integration, vertical as well as horizontal, the proposed method is using the system elements to design and develop the subsystem components. More specifically, the vertical integration is achieved through a direct link between the subsystems and their common higher level system. Details about how this can be achieved are presented in the obesity example.

Additionally, the horizontal integration is realized through having common high levels goals for all the related subsystems while also being able to maintain their own identity and applicability based on the particular characteristics.

An example is used in the subsequent chapters for introducing the methodology. It is generally recognized that obesity is one of the biggest pandemics of our time. In general, although it is well recognized that the obesity is a major driver for other medical conditions, from the system perspective it is still seen as a standalone entity. Unlike that that perspective of obesity being an independent entity, the present research effort proposes a methodology that suggests addressing the obesity problem initially by looking at the higher level prevention system in order to establish a more holistic approach. There are several recognized arguments that support this approach.

First and foremost, obesity is not the only preventable disease inflicting the public. In other words, obesity is arguably just a piece of a system that includes other similar subsystems. There are several other illnesses and conditions (e.g. high blood pressure, diabetes, high cholesterol, etc.) that can be proactively managed, or even prevented or eliminated by individuals pursuing a lifelong personal health strategy. By understanding the needs of the prevention system, the needs of the subsystems can be better identified and aligned to the systems' needs.

Secondly, having a standard methodology makes the development of other subsystems much more consistent. As a matter of fact, as it is seen in the example used in this work, the development of another subsystem based on a different preventable disease not only can follow the same methodology, but can also draw the higher level needs directly from the higher level prevention system. There are no significant changes

anticipated in what the stakeholders expect at a high level (e.g. security, public policy support, affordability, etc) within the top system level.

Thirdly, by using sound design concepts in healthcare system development the solutions identified are based on evidence and driven by the data rather than just experience or anecdotal knowledge. A data driven system design is a prerequisite to a data-driven decision making system. The high focus of system design on stakeholder needs is as critical in a healthcare system development as it is in any other field.

The core of the system design methodology used in this research is based on System Analysis and Design methodology (Akao, 1990) (Blanchard & Fabrycky, Systems Engineering and Analysis, 2011) (Breyfogle III W. F., 2003). The most critical part of the methodology, affecting all the others, is the understanding of the system requirements that would meet the VoC, which expresses customer's wants and needs. More than in product or process design, in system design there is rarely one unique customer, particularly for major systems. A system of the complexity of the healthcare prevention has several major stakeholders that, when combined, provide the VoC. Among these stakeholders, the most important is obviously the general public which also plays a dual role as the beneficiary as well as the sponsor of the system. Other stakeholders are the medical professionals, governmental institutions, insurance companies, among others. The translation of multiple VoC into a robust healthcare system design can be achieved through the use of specific system design concepts. Quality Function Deployment is the basic tool as introduced in (Akao, 1990). By using sound system design principles the likelihood of identifying solutions that generate customer satisfaction increases considerably.



According to (Blanchard & Fabrycky, 2011), the definition of systems engineering and the systems approach is usually based on the background and experience of the individual or the performing organization. One way of distinguishing between different types of systems, is the dichotomy of static (constant in time) versus dynamic (time related). A static system is one whose states do not change because it has structural components but no operating or flow components, as exemplified by a bridge. A dynamic system exhibits behaviours because it combines structural components with operating and/or flow components. An example is a school, building, students, teachers, books, curricula, and knowledge.

The motivation of modeling obesity as a dynamic rather than static system emerged from considering it in a dynamic relationship with other factors that contribute to its development. Also, obesity is fundamentally related to time which by definition is the main characteristic of a dynamic system. The individual becomes an active part of the decision making process. The individual dynamically participates in not only the development of the strategy, but also by intervening continuously in adapting it based on the actual results and needs.

In Figure 12 the system/subsystem developmental levels are introduced. The identification of stakeholders needs is a common step for both.

The methodology proposed in this work suggests five levels of development of a system, particularly suitable in healthcare: Level 1 to 5 (L1 to L5). The methodology proposes the identification and development of the higher level system first. Level 1 (L1) is the system level that oversees all the subsystems related to it (Figure 12). The next four

levels belong to the subsystems. The four levels should be standard and followed for the development of each of the subsystems.

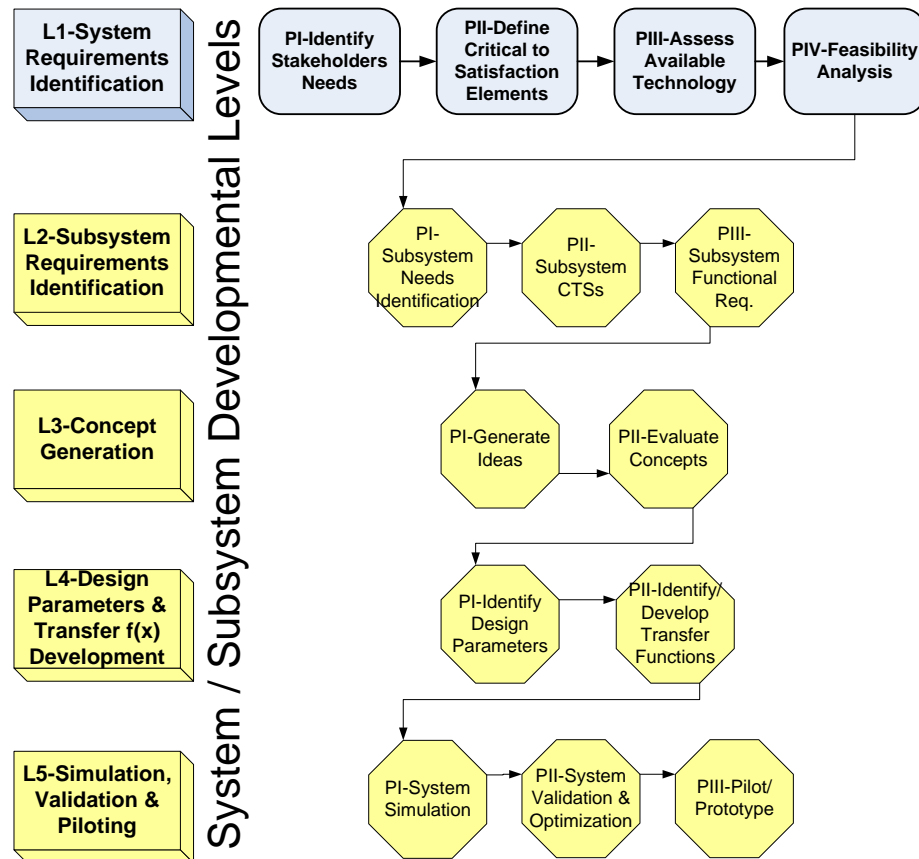


Figure 12 – System / Subsystem Developmental Levels

The sequence within the levels should also be followed. Consequently, only after completing the four phases (Phase I to IV) of the system level the system designer must progress to the first subsystem (L2) and complete the three phases (PI to PIII) identified on the flow chart. The cycle continues to the next lower level only after the completion of the two phases of the current level. A more detailed description of the levels and phases follows in the subsequent paragraphs.

As mentioned previously, the subsystem design proceeds with analyzing the higher level system. Particularly in the System Requirements Identification, very thorough research and analysis of the VoC from the system perspective must be employed. The four phases of the system level preliminary design are:

- L1-PI: The Identification of the Stakeholders Needs – What is the VoC? What is required from the system in order to meet the stakeholders' requirements?

This is a very intensive phase where more traditional system design tools are employed such as surveys, interviews, focus groups, etc. Out of all the system design phases, the front-end efforts related to fundamentally understanding the VoC is arguably the single most important step since it helps set the direction for future work. The success of the entire design process depends largely on how well the VoC is identified and processed. When considering the example used in this research (the healthcare prevention system), theoretically stakeholders consist of the entire population where every individual either benefits or participates directly, although the levels of engagement may vary. Consequently, as it is underscored in the subsequent chapters, a wider effort was engaged in learning from various sources about what a prevention system would need to provide in order to be of benefit to a large proportion of the population. Recent and older articles were identified, including research papers in the field of prevention of obesity, as well as informal and formal conversations with various stakeholders of such a system, including students, medical personnel, researchers and even the general public, friends and acquaintances.

- L1-II: Critical to Satisfaction (CTS) Elements – Based on the identified needs, this element is used to define ways of quantifying the VoC. With this approach, the measurement system, as an integral part of the overall system, is linked directly to what it is supposed to measure: how well the system design meets the expressed needs of the stakeholders. The integration of the VoC and CTS is done through what is known in system design methodology as the Quality Function Deployment (QFD) or House of Quality approach. More details about the QFD follow.
- L1-PIII: Assess Available Technology – High level research in the available technology based on the data obtained from the previous elements allows for the identification of possible gaps that might hinder a future solution. The technology might be readily available (mature), in the process of becoming available (discovery stage), or unavailable (where a viable alternative should be sought).
- L1-PIV: Feasibility Analysis – At the system level, early stage analysis for the feasibility of the system prevents further progress in cases when there are no feasible solutions. The feasibility is strictly related to the higher level system since it does not contain sufficient detail, nor that it should, of the subsystems soon to be developed.

The beginning of the subsystem design is similar to that of the system. It means that, what was learned from identifying and analyzing the system level VoC is used to identify the particular needs and develop the design on a subsystem level. In fact, the subsystem's needs emerge from the system development as illustrated in the obesity

example. In view of the proposed methodology, this is done seamlessly and naturally while avoiding an artificial separation between the subsystem and the system from which it emerged. Particularly, while the system's first two phases are Stakeholders Needs Identification (PI) and Critical to Satisfaction Elements (PII) definition and development, the subsystem's first two phases are virtually identical. However, they are addressed at a lower and more specific level.

After the first two phases included in the Subsystem Needs Identification level, L2 is concluded by the development of the Functional Requirements (FRs) phase (LIII). FRs answer questions related to what the system needs to do. What is the functionality of the system in development?

L3 for Concept generation and has two phases:

- L3-PI: Generate Ideas – With the information discovered in L1 & L2 several possible solutions for the subsystem design can be identified. Particular system design tools are used for this purpose and are introduced in the subsequent example.
- L3-II: Evaluate Concepts – The possible solutions identified during the previous stage are evaluated and ranked based on the CTSs developed in earlier stages. The concept (or a combination of concepts) that meets most of the stakeholders' needs is identified in Level 4.

By identifying the best solution in the next level, the Design Parameters (DPs) and Transfer Functions (TF) are developed or identified in Level 4.

- L4-PI: Design Parameters – This level of detail is required for understanding how the final system meets the stakeholders' needs. In our case, the DPs define

the foundation for identifying the transfer functions that become the foundation for the simulation model.

- L4-PII: Identify/Develop Transfer Functions – This is the translation of the DPs in quantitative functions that are subsequently used in simulating the system. A detailed introduction of the TFs follows in a future chapter.

The last level (L5) is Simulation, Validation and Piloting. The TFs developed in the previous step are introduced in a model for attempting to simulate the behavior of the system. The three elements of this level (System Simulation, System Validation and Optimization and Piloting/Prototyping) are further discussed in the obesity example.

### 3.2. Quality Function Deployment

The main concept used in the initial development of the AMHSC is Quality Function Deployment (QFD) (Akao, 1990). QFD provides specific methods for ensuring quality throughout each stage of the product development process, starting with design. In other words, this is a method for developing a design quality aimed at satisfying the consumer and then translating the consumers' demand into design targets and major quality assurance points to be used throughout the production stage. While QFD concept is widely used in product/process design, its application in a healthcare prevention system design is characteristic to this research.

In general, it is recognized that the application of QFD in non-industrial environments presents challenges (Dijkstra & van der Bij, 2002). The approach proposed in this work not only applies QFD in a non-industrial case, particularly healthcare

environment, but also integrates what traditionally would have required separate QFDs in one unique method.

As discussed in Chapter II, there are examples of QFD use in healthcare (Omachonu & Barach, 2005), although it is identified as a rare occurrence, especially based on the approach proposed for the present healthcare system design.

### 3.2.1. House of Quality 1 (HOQ1)

In Figure 13, the first House of Quality (HOQ1) is presented. HOQ1 is used to correlate the macro system's VoC (the left hand side list) to the CTS elements (top list). The roof of the house illustrates the tradeoffs among the CTSs. The right hand side, the Pareto chart, lists the VoC elements in the order of importance, based on the aggregate correlation scores. The Pareto chart at the bottom side of the house provides the order of importance for the CTSs. A more detailed analysis is presented in the following pages.

The following points can be considered for developing correlation between the CTSs and VoC elements represented in the central elements of Figure 13:

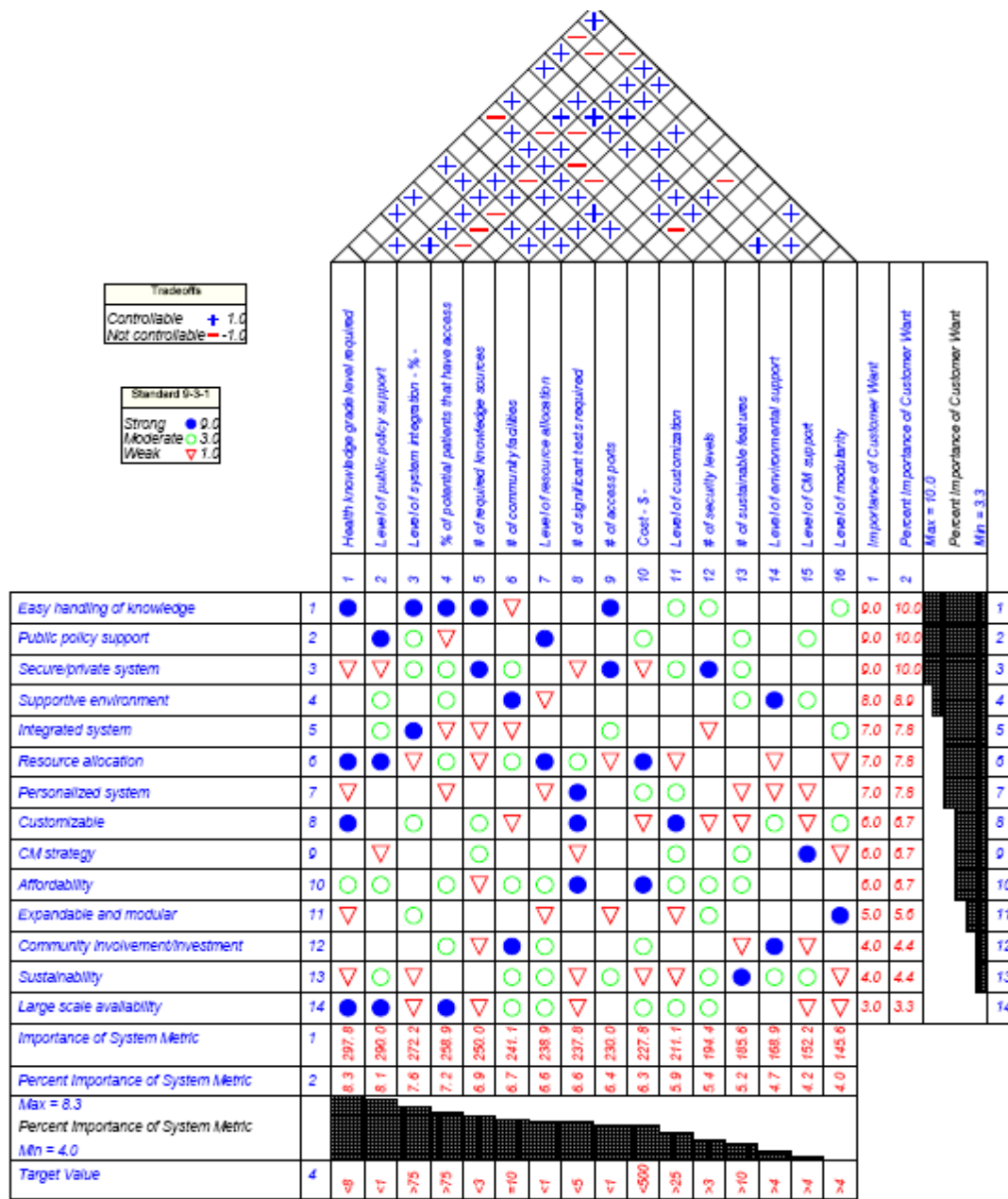


Figure 13 - HOQ1 VoC vs. CTSs correlations

- The left side list or column presents the VoC. As mentioned before, the customer needs for the macro-system emerged from researching various sources of knowledge including publications, articles, research papers, formal and informal surveys and discussions, conversations with healthcare



professionals and others. For a system of this type, there are multiple stakeholders including the general population, healthcare professionals, insurance agencies, government, etc. During the first stage of the system development, the focus is primarily on the population needs. Those needs are listed in the descending order of importance, starting from the top.

- The list or row presented at the top of Figure 13 shows the CTSs metrics or, in other words, how the VoC items are measured. They are also listed in descending order of importance, starting on the left hand side of the list. More explanation is provided below.
- The central matrix shows the strength of the correlations between the CTSs and the VoC. The matrix illustrates how well each of the CTSs correlates with each of the VoC elements. The analysis relies on a mix of qualitative and quantitative approaches. Each of the symbols represents specific correlation strength. While a (9 – 3 - 1) scale of use for easier differentiation is available, the system designer can adjust it according to the preferences. The choice of the scale depends on how much resolution the particular study offers. Smaller steps on the scale, more difficult becomes in certain cases to differentiate between the elements. The symbols that appear in the matrix can be interpreted as follows:
  - Blue color full circle – Strong correlation or the particular metric measures directly with the corresponding VoC element – Score: 9 (in this case only; it can be changed);

- Green color empty circle – Moderate correlation or the particular metric measures indirectly with that particular VoC element – Score: 3;
  - Red color empty triangle – Weak correlation where there is a relationship between the CTS and the particular VoC element – Score: 1;
  - Empty cell at the intersection of any CTS with any of the VoC elements – No relationship between them – Score: 0.
- It is desirable that, each VoC is measured by at least one CTS. As it can be seen from the matrix, this condition is met since there are no empty rows in the matrix.
  - The lack of empty columns in the matrix reveals that all CTSs pertain to a non-zero set of the VoC elements.

On the right hand side of Figure 13, a Pareto diagram of the VoC elements in the order of significance is presented, based on the correlations with the CTSs. By analyzing the outcome, the following can be concluded:

- The most important VoC elements are:
  - Easy handling of knowledge – In order for this system to be used as intended, the information needs to be presented at a proper level of user understanding. There is currently an overwhelming amount of information available and various sources from which it can be acquired. Oftentimes the information is not at the level required for the general public comprehension, either due to the advanced medical content or form, requiring advanced technology for interpretation (e.g., computer system,

Internet access, specialized software, etc.), for which not all users have at the same level of proficiency or equipment access.

- Public Policy Support – Although the system is conceptually designed to be personalized (Bacioiu & Pasek, 2010) for each individual, the manager of the healthcare system (the Government of Canada) needs to support the prevention system by introducing appropriate policies and procedures.
- Secure/private System – This is another critical element for which its position on the scale is easy to justify. Since the system is meant to be either personalized or customizable, personal information used in order to adapt it to the particular needs of the individual. The way this confidential information is handled and protected is very important.
- On the other side of the spectrum, Community Involvement/Investment, Sustainability and Large Scale Availability scored the least number of points. This does not necessarily mean that they are not needed but rather they can be implemented or addressed after the major needs of the system are fulfilled.

Similarly, with the VoC ranking, Figure 13 includes a Pareto chart of the CTSs metrics. It is important to know which of the CTSs are measuring multiple needs. A very common concern for system design is in first identifying then addressing the coupling between the CTSs. The more customers needs a specific CTS metric measure, leads to more opportunities for coupling to occur.

Alternately, it is not necessary to include measures of the VoC – alias CTSs – if they are not truly a measure of anything, or if the measure of a need is very weak while that particular need is also measured by other CTS elements. However, if the customer's

need is not measured by any of the CTSs, this should also signify that it cannot be assessed or improved.

The Pareto chart at the bottom of Figure 13 visually demonstrates the significance of the CTSs beginning with the most significant (Health Knowledge Grade Level Required) to the least important (Level of Modularity) flowing from left to right on the graph. A quantitative measure for the system metrics importance and relative percentages are also introduced based on the correlation matrix.

The important points to consider are as follows:

- Health Knowledge Grade Level Required is the most essential CTS. This means that the metric is critically important in measuring multiple elements of the VoC. At the very bottom of the figure, there are targets to achieve for each of the metrics. In this case, the target as part of the prevention system must allow for the information to be “translated” or adapted at a maximum Grade 8 student level of understanding. Therefore, most if not all of the population should be able to understand and use the information provided.
- The second most important CTS is the Level of Public Policy Support. As the system is meant to be adopted by the general population, it is critically important to have the Government’s support in deploying the appropriate policies.
- Level of System Integration – There may be a number of subsystems and several components of the different elements of the prevention system simultaneously operating. In order for the prevention system to be adopted, all these subsystems must be compatible, integrated and synchronized. The

adopters are neither willing, nor knowledgeable enough in general, to assemble the pieces together on their own. This means that they do not want access to multiple subsystems concurrently in an effort to find the correct solution or even a listing of options available to their specific situation.

- At the other end of the Pareto chart, Level of Environmental Support, Level of CM Support and Level of Modularity do not address multiple needs. Again, this does not mean that they lack importance. If the correlation matrix in Figure 13 is closely examined, it can be noted that although they do not measure multiple needs of the customers, they strongly correlate with at least one need. Consequently, they must be kept as part of the system.

Figure 13 provides evidence for the tradeoffs among the CTSs in the “roof” of the house. The symbols in the matrix have the following meanings:

- Blue “+” symbol – Indicates a positive correlation between the respective CTSs. In other words, if one is changing towards the “positive” or “good/wanted” direction, the other CTS does the same. Alternately, if a CTS moves towards the “negative” or “bad/unwanted” direction, the other follows similar trend.
- Red “-“ symbol – Represents a negative correlation between the respective CTSs. This is to say that one flows towards the “positive” or “good/wanted” direction, while the other does the exact opposite by changing towards the “negative” or “bad/unwanted” direction.
- Empty cells at the intersection of any pair of CTSs indicate a lack of relationship between the two CTSs.

Challenges occur when negative correlations between the CTSs exist. In other words, a negative correlation leads to degradation of one element whenever improvements are made to another. Such tradeoffs need to be addressed appropriately.

The well-known and accepted methodology for eliminating these tradeoffs is Axiomatic Design (Suh, 2001). According to this approach, there are two axioms that create the theoretical foundation for axiomatic design:

- i. Axiom 1: The Independence Axiom. Maintain the independence of functional requirements.
- ii. Axiom 2: The Information Axiom. Minimize the information content.

For the case in question, the system tradeoffs need to be addressed before the system implementation by either using the principles and methodology of Axiomatic Design or some other system design concept, such as TRIZ. Through a simple review of the tradeoffs matrix in Figure 13, it can be readily noted that the people's access to the system generates the greatest number of conflicts. Adjacent to this area is the Level of Customization and Level of CM support, both of which generate additional conflicts that must be addressed. A brief analysis of the matrix includes the following:

- The number of potential users having simultaneous access is negatively correlated with the number of allocated resources. A growing number of system users drives the need for more resources but this does not improve the overall metric. For the system to be feasible and cost effective, resource use/consumption must be minimized. Similarly, cost is negatively correlated with the Number of security levels since more security leads to, at least in short term, more cost associated with the building and operational systems.

- The level of system integration is positively correlated with the fraction of the population having access. The reason for this fact is that, if the system is integrated, less learning is required by each user.

All other pairs of data can be analyzed by using the same logic as in the examples above.

### 3.2.2. House of Quality 2 (HOQ2)

HOQ2 is the link between the macro system and a subsystem chosen for the purpose of applying the proposed methodology of obesity. The CTSs generated by the VoC of the macro system are correlated with the high-level elements of the obesity subsystem.

Traditionally, QFD is used for product development, essentially for creating a logical path that links the VoC to the CTSs and further develops towards the Functional Requirements (FRs) of the particular design and Process Variables (PVs). In this way, there is a direct connection between the final product or service and what the customers need.

In this research, not only was the traditional QFD used for system development and design rather than product or process, but it was also used to integrate the macro-system with one of its subsystems. A more detailed analysis of this approach for using QFD in system-subsystem integration is provided within a subsequent chapter.

An overview of HOQ2 is shown in Figure 14.

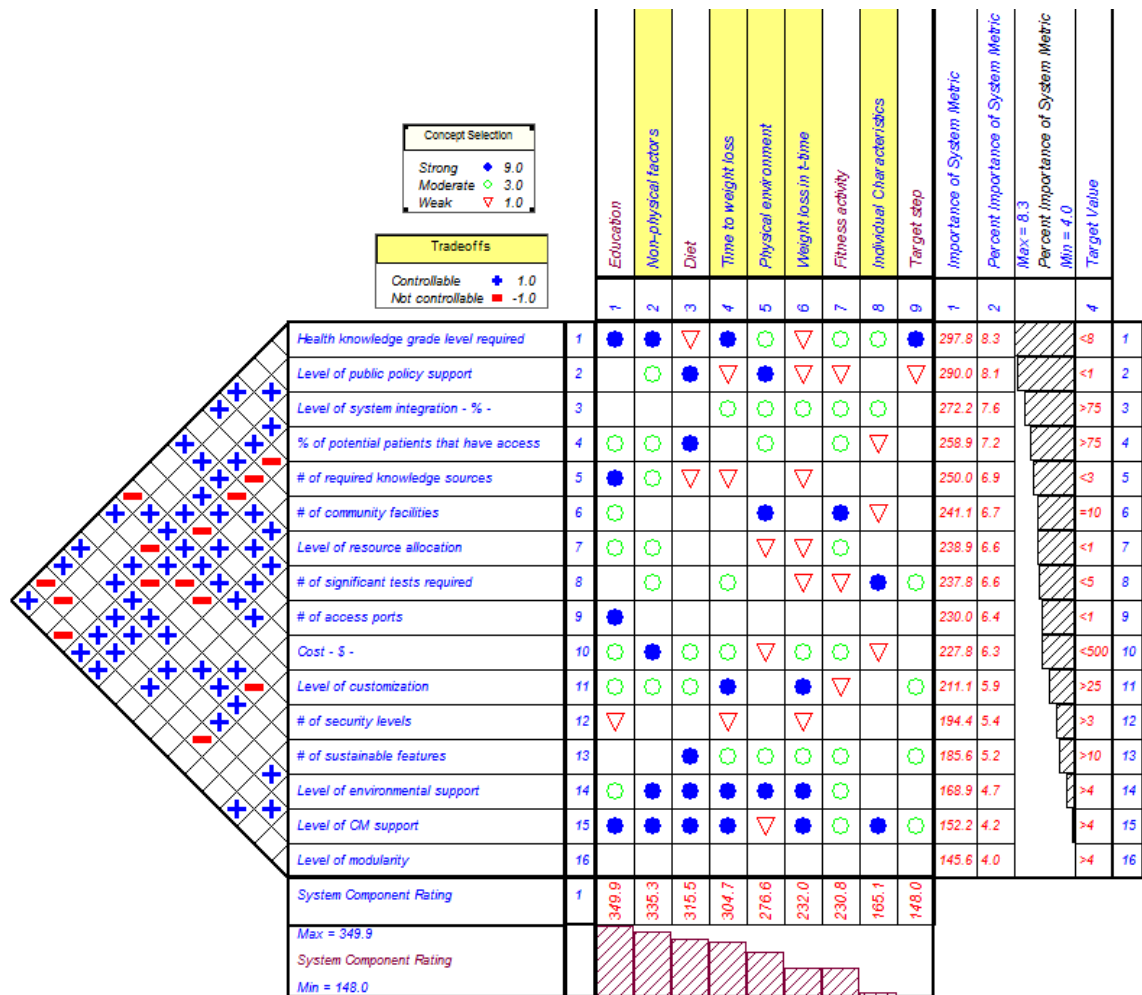


Figure 14 - HOQ2 System to Subsystem Integration

The left hand side of Figure 14 is created out of the CTS elements identified and correlated with the VoC in the macro-system. Listed at the top are the high-level elements of the obesity subsystem, including both inputs and outputs of the system. The high-level inputs are as follows:

- Education – in the field of obesity and as a system element rather than level of knowledge
- Diet – one of the major elements of the subsystem
- Fitness – again, as a system element rather than level of achievement



- Physical Environment – the living surroundings of the individual
- Individual Characteristics – including the level of education, family history, initial weight etc.
- Non-physical Factors – including motivation, emotional state etc.
- Target Step – the element of the system that controls the adjustment towards the desired outcome

There are two outcomes of the subsystem that were included in the matrix and correlated with the macro-system as follows:

- Time to Weight Loss – if the target is defined as a certain amount of weight loss, what is the amount of time necessary to achieve it?
- Weight Loss in Time – alternately, if the target is expressed as a certain time, what is the achievable weight loss required?

The outputs of the subsystem dynamically depend on the inputs listed above.

From the analysis of the HOQ2 perspective, and considering that the approach is similar to the analysis presented for HOQ1, it can be noted that all the elements have at least one strong relationship, with the exception of the Level of Modularity which has no direct correlation to the macro-system. It may be concluded that, by addressing the subsystem elements, there is a direct connection to the macro-system needs. Particularly by designing a system that supports a reduction or elimination of the obesity pandemic, the prevention system also improves and vice-versa. This is a very significant advantage for the methodology suggested in the system-subsystem integration since they directly correlate. This is in fact the logical approach for developing a subsystem; it is not a separate entity but rather one emerging from the system in which the subsystem belongs.

At the bottom of Figure 14, a Pareto chart of the obesity system (OS) elements based on the correlations with the macro-system is presented. The top three elements are as follows:

- Education – Understanding and acquiring knowledge about obesity is one of the key elements of following, implementing and sustaining the subsystem at the personal level
- Non-physical factors (such as Motivation, Stress etc.) – (Rutters, Nieuwenhuizen, Lemmens, Born, & Westerterp-Plantenga, 2008) and others confirm the top position for this system element as critically important to the success of the OS adoption
- Diet – the system element that is most significantly associated with obesity

### 3.2.3. House of Quality 3 (HOQ3)

An overview of HOQ3 is presented in Figure 15 that illustrates the high-level OS elements correlated with OS variables, both endogenous and exogenous. This is the next level of detail where the high-level system elements are decomposed. The initials before each factor indicates the higher-level system element to which they are linked as follows: E – Education; NPF - Non-physical Factors; D – Diet; PE – Physical Environment; FA – Fitness Activity; IC – Individual Characteristics.



A similar method of analysis as presented in HOQ1 should be considered here. A few key conclusions based on the correlation matrix include the following:

- There is a strong correlation between the outputs and subsystems elements.

This is expected considering that the goal of the system design is being able to predict the output based on the inputs identified.

- The majority of the subsystem inputs are correlated with at least one additional high-level OS element beside its own. Note that the inputs were purposely not correlated with the originating OS elements as obvious correlation existed
- The only three inputs that correlated only with their own sources included: IC – Social/Economic status, IC – Education Level and IC – Family History. All others inputs had at least one strong correlation with another group.

The inputs are split in to endogenous (dynamically controlled as part of the Obesity System) and exogenous (inputs that remain constant).

A description of the factors follows in Chapter IV.

### 3.3. Pugh Matrix and Morphological Matrix – HOQ4

The Pugh matrix (Decision-matrix method, 2001) is also known as the decision-matrix method, Pugh method and Pugh Concept Selection. It is a quantitative technique used to rank the multi-dimensional options of an option set. Frequently, it is used in engineering for making design decisions but can also be used to rank investments options, vendor options, product options or any other set of multidimensional entities.

A basic decision matrix consists of establishing a set of criteria upon which the potential options can be decomposed, scored, and summed to gain a total score, which

then can be ranked. Importantly, the criteria are not weighted to allow for a quick selection process. The advantage of this approach to decision making is that subjective opinions about one alternative versus another can be made more objectively. Another advantage is that sensitivity studies can be performed and analysed. An example of this could include observations for noting how much an individual's opinion would need to change in order for a lower ranked alternative to out rank a competing alternative.

In (Burg, Hill, Brown, & Geiselhart, 1997), the authors demonstrated an application of a Pugh Evaluation Matrix, which helped them estimate the effects of each technology on the overall system and their impact on the design requirements. Pugh Matrix was used similarly in this work with the only exception being the application in a healthcare system design rather than an industrial application. Pugh Matrix was used in identifying and synthesizing suitable designs for the obesity system.

Before building the Pugh Matrix for synthesizing possible solutions to obesity pandemic, the Morphological Matrix was used. In Table 4, the first left hand side column represents the needs of the system. The needs can be fulfilled in a number of different ways or for the majority of the cases there are multiple solutions to each unfulfilled need.

In Table 4 the rows represent an example of alternative solutions for each need. The designer and stakeholders attempt to generate different combinations of the alternatives in order to feed the Pugh Matrix and identify the best overall solution for the obesity system.

Table 3 - Morphological Matrix

System requirements	Possible system solutions that would address the system requirements				
NPF- Create Motivation	Governmental Program	Change Management tools	Financial constraints/ incentives	Workplace wellness	Education on risks associated
NPF- Provide Emotional Support	Create focus groups	Change Management tools	Emphasis on family	Organized group support meetings	
D- Reduce food intake	Advertisement	Financial constraints - e.g. high taxes, etc.	Education on proper food portions	Emphasis on family	
FA- Reduce sedentary time	Parks and recreation centers	Financial incentives	Workplace wellness	Government funded exercise programs	
D- Improve Diet Quality	Financial constraints - e.g. high taxes on unhealthy food, etc.	Advertisement	Funded programs on benefits of proper diet	Encourage personal gardens, orchards, farms	
FA- Increase Cardio	Cardio equipment in public places	Financial incentives	Cardio equipment on site in the workplace	Organize public activities	
E- Provide Dietitian &/or Trainer	Governmental funding	Weight loss programs @ workplace			
Set Target step	Set by dietitian	Set individually	Set by family		
E- Encourage Self - study	Learning system	Study groups	Family education	Workplace wellness	
E- Create Study groups	Based on social media - e.g. Facebook etc.	Based on community centers	Workplace wellness	Family program	
FA- Encourage Strength Training	Financial incentives	Strength equipment in public places	Strength equipment on site in the workplace		

Possible Solutions

Red: Government

Blue: Social

Green: Constrained

Black: Workplace

In this particular case, there are four potential subsystem design solutions based on different combinations of the system requirements. The identification of the potential solutions was done through consulting either healthcare professionals or other individuals not necessarily directly involved in the healthcare system as providers. That is considering the particularities of the prevention system that has multiple customers, theoretically, as well as practically, the whole population. The grouping/clustering of the solutions under different clusters is not unique. The clusters attempt to suggest different directions, particularly during the implementation phase, which was not one of the goals of this thesis.

The names of the solutions provide hints about their nature. For example, Governmental based solution selects the elements that are related highly to the role the Government plays in the overall system. The Constrained solution attempts to select

elements that would “force” the promotion and implementation of a preventive system, particularly in obesity management. As an example of the solution identification process, four of the potential solutions are listed below:

- Governmental Based - Governmental Program, Change Management (CM) Tools, Advertisement, Parks and Recreation Centers, Advertisement, Cardio equipment in public places, Governmental Funding, Target by dietician, Learning systems, Based on Community centers, Strength equipment in public places
- Social Based - CM Tools, Focus groups, Education in food portions, Financial incentives, Personal gardens/farming, Public activities, Governmental funding, Target set individually, Study groups, Social media, Workplace strength equipment
- Constrained - Financial Constraints or Education on risks, CM Tools, Financial constraints, Workplace wellness, Financial constraints, Financial incentives, Weight loss program at workplace, Target set by family, Family education, Workplace wellness, Strength equipment in public places
- Workplace - Workplace wellness, Group support meetings, Education on food portions, Workplace wellness, Funds for programs on diet, Cardio equipment on worksite, Weight loss programs at workplace, Target set by dietician, Workplace wellness, Workplace wellness, Workplace wellness, Strength equipment on site of the workplace.

The Pugh Matrix presented in Table 5 helps in the evaluation of the concepts against a known standard. Usually the benchmark is either the best in class similar system

or the current state of the system in place. In this case, the Governmental based solution was considered the datum and the others were evaluated against it.

Table 4 – Pugh Matrix

Concept	Import. Rating	0	1	2	3	4	
CTSSs							Financial constraints or Education on risks
NPF- Create Motivation	5.5		+	S	S	+	Change
NPF- Provide Emotional Support	4.9	D	S	+	S	+	Management tools
D- Reduce food intake	4.2	A	+	S	+	+	Education on proper food portions
FA-Reduce sedentary time	4.2	T	S	S	S	S	Parks and recreation centers
D-Improve Diet Quality	4.2	U	+	+	S	+	Encourage personal gardens, farms
FA- Increase Cardio	4.1	M	S	+	S	+	Financial incentives
E- Provide Dietician/Trainer	4.4		S	+	S	+	Weight loss programs @ workplace
Set Target step	3.8		+	-	+	+	Set individually
E-Encourage Self -study	3.1		+	S	+	+	Study groups
E-Create Study groups	3		S	S	S	S	Based on social media - e.g. Facebook
FA- Encourage Strength Training	1.8		S	S	S	S	Strength equipment in public places
			5	4	3	8	
Σ-			0	1	0	0	
ΣS			6	6	8	3	
Best Cases		Major Strengths	Major Weaknesses				
1-Social		Engage the social power, less constrained and more on a volunteer basis, individual commitment etc.	Too much based on volunteer commitment. Some people do not have the strength				
2-Constrained		Attempts to hit a sensitive point by either rewarding commitment or penalizing for not engaging in wellness activities.	Not a popular approach				

The functional requirements identified are listed on the left hand side column. The imported ratings from the HOQ3 are located in the second column, whereas the column labelled Datum includes the Governmental based solution that was chosen in the absence of a clear and unique benchmarking or current system. The next three columns labelled 1, 2 and 3, respectively, are the other three solutions identified: 1- Social Based, 2 – Constrained, 3 - Workplace.

The “+” sign represents an element of the respective solution that is better than the datum. Similarly, “S” means that the element is the same, where it is no better or



worse. A “-“ sign indicates that the particular element is less desirable than the datum. At the bottom of the table, the sums for the “=”, “S” and “-“ in each column are shown.

The best choice, considering all scores, appears to be the Social based case as it has the most number of elements better than the datum. That is, there are 5 plusses, 0 minuses and 6 the same as the datum. However, the best approach is to investigate further each alternative and identify its potential strengths, so that once they are combined, it creates the ultimate and comprehensive solution. For the case in question, it is labelled as 4, coloured grey in the Pugh Matrix and described with each element on the right hand side attachment. This is illustrated in Table 6.

Table 5 - Chosen Solutions for Each CTS

System requirements	Possible system solutions that would address the system requirements				
NPF- Create Motivation			Financial constraints/ incentives		Education on risks associated
NPF- Provide Emotional Support		Change Management tools			
D- Reduce food intake			Education on proper food portions		
FA-Reduce sedentary time	Parks and recreation centers				
D-Improve Diet Quality				Encourage personal gardens, orchards, farms	
FA- Increase Cardio		Financial incentives			
E- Provide Dietitian &/or Trainer		Weight loss programs @ workplace			
Set Target step		Set individually			
E-Encourage Self - study		Study groups			
E-Create Study groups	Based on social media - e.g. Facebook etc. -				
FA- Encourage Strength Training		Strength equipment in public places			

The method used for generating and synthesizing designs by using Morphological and Pugh Matrixes is considered traditional, though, they are not used very often in

system design. However, an adjustment of the QFD process can lead to the same results. Particularly, by modifying one of the houses to accommodate the elements of a Pugh Matrix the necessity of having separate entities vanishes. In Figure 16, the QFD based Pugh Matrix is presented.

Similarly to the case explained before, the Governmental based solution is the Datum. The rest are evaluated based on how they meet the requirements compared to the datum.

		<div> <div> Concept Selection </div> <div> Better <span>◆</span> 9.0  The same <span>◇</span> 3.0  Datum <span>★</span> 1.0  Worse <span>▼</span> 0.0 </div> </div>				
		Government based	Social based solution	Constrained approach	Workplace based	Combination
		1	2	3	4	5
NPF- Create Motivation	1	★	◆	◇	◇	◆
NPF- Provide Emotional Support	2	★	◇	◆	◇	◆
D- Reduce food intake	3	★	◆	◇	◆	◆
FA-Reduce sedentary time	4	★	◇	◇	◇	◇
D-Improve Diet Quality	5	★	◆	◆	◇	◆
FA- Increase Cardio	6	★	◇	◆	◇	◆
E- Provide Dietitian/Trainer	7	★	◇	◆	◇	◆
Set Target step	8	★	◆	▼	◆	◆
E-Encourage Self -study	9	★	◆	◇	◆	◆
E-Create Study groups	10	★	◇	◇	◇	◇
FA- Encourage Strength Training	11	★	◇	◇	◇	◇

Figure 16 – QFD based Pugh Matrix

The system design process supported this work in two ways:

1. The identification of the modeling parameters emerging directly from the VoC not only of the subsystem but also of the higher level system (prevention). This outcome of the system design process was pursued further by building the structural model first and then using the System Dynamics concept to simulate the behavior of the human body from the obesity perspective. That allowed for a direct link between the outcome, that is the simulation parameters that generated the obesity model, and the input, which was the VoC not only at the subsystem but also at the system level.
2. The second way the system design process was in support of this work was by identifying potential solution for policy design and implementation. While the information is valuable, this part was not pursued further at this point and through this work due to the level of resources required to do a thorough VoC identification and analysis and develop policies at all levels in support of the implementation of the final system design solution. It might become the scope of a future work.

### 3.4 Evidence Based Decision Making (EBDM)

EBDM is a relatively new concept. It has different branches that each adapt the overall concept to the needs of specific focus (e.g. Evidence Based Design, Nursing, Medicine, etc.).

(Davidoff, Haynes, Sackett, & Savage, 1995) claim that doctors need to understand the studies that demonstrate whether new ideas work, but their volume has grown enormously. This research is following the same beliefs and attempts to either integrate sound research in the development of the final system or, alternately, provide individuals with guidelines for obtaining accurate information when the need occurs.

In 1991 the American College of Physicians began a journal entitled ACP Journal Club, which aimed to provide doctors with up to date information. The editorial team screens far more journals than the average doctor can ever hope to read, and identifies research articles of potential clinical relevance. The team also scrutinizes the research methods used in these studies and rejects those having conclusions that are likely invalid or inapplicable.

The research proposed in this dissertation is aligned to the definitions and purposes of EBDM philosophy. Moreover, it is the researcher's belief that it goes beyond what is traditionally known as EBDM considering that not only the decisions are made based on sound research, they are also considered even before the need to make decisions occur by incorporating the concept in the early system design phase. The methodology presented allows the design, implementation and use of the system based on evidence. More specifically, the identification and development of the system, based on the VoC, uses proven concepts to systematically build the evidence relative to the data and sound research. From the early stages of the system design process all the way to the transfer functions used and the integration of different elements, data based decision making is employed.

In Figure 17 the transfer of knowledge for an evidence based approach is presented from the initial stage of the design process to the use of the model.

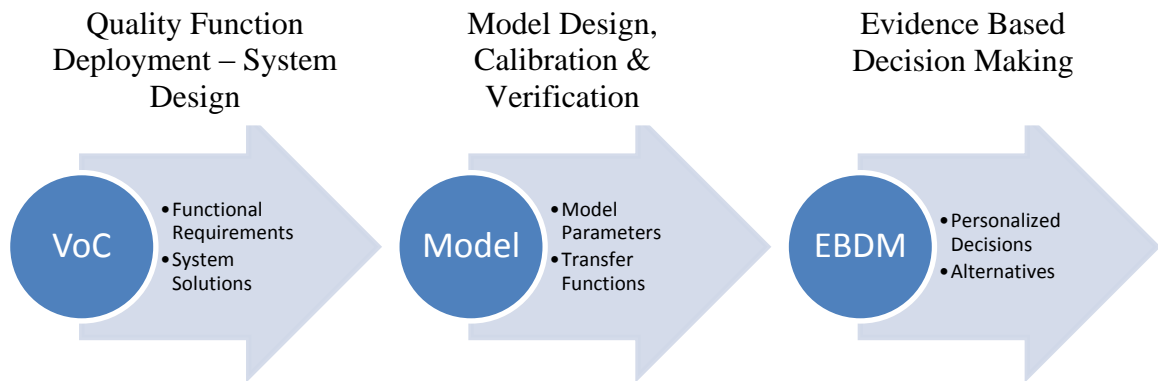


Figure 17 – Link between Research Elements

By following a robust system design process the probability of success in the development of the functional requirements as well as in the identification of the system solutions increases. Furthermore, system design is a methodology that can be applied consistently not only in the development of an obesity model but it might also be used in other medical conditions. The developer can adjust the different components starting with the VoC and identify the FRs as well as system solutions for other particular cases by following the methodology.

If the system design process is pursued, the model structure becomes transparent and follows the outcomes of the process. QFD provides a structured process that allows the identification of the modeling parameters. The model parameters are linked to different requirements of the system, which may or may not truly reflect the reality. The transfer functions quantify the system elements in an analytical fashion and are developed based on scientific research.

Through following the first two major stages proposed in this work, the final tool used by an individual to control the weight loss/maintenance emerges as a result of scientific research and approaches rather than common sense or what is commonly known as accepted knowledge. While the methodical approach has the potential to provide superior solutions comparing to the use of only intuition, the engineered truth is still not perfect and is only an approximation of the reality. Concurrently, by following a standardized process, should any of the elements change either by the researchers acquiring new scientific understanding, or by the customers/patients changing their needs, it offers a clear way of addressing the respective change by amending the required elements. Also, the design process that can identify the blocks that are potentially needed, must be complemented by an analysis of the blocks that are already in place.

Understanding the present helps in sketching the future.

From this sequence perspective, the first part of the block diagram illustrated in Figure 17 was presented in this chapter. In the ensuing chapters, the last two elements are discussed: Model Design, Calibration & Verification and EBDM related to obesity condition.

## CHAPTER IV

### STRUCTURAL MODEL DEVELOPMENT

#### 4.1. Obesity System Structural Model & Parameters

This research is proposing that the system design should start from a higher level. By understanding the higher level system, not only will the needs of the subsystems become directly aligned to what is critical at the higher level but it also allows for a standard application of the methodology to any other subsystem of the system in discussion.

The starting point of developing the structural model was based on the outcome of the system design effort. In other words, the inputs of the structural model emerged from what was identified by the system design as being critical to the customers. A high level diagram that shows the transition from the design to the modeling phases is presented in Figure 18.

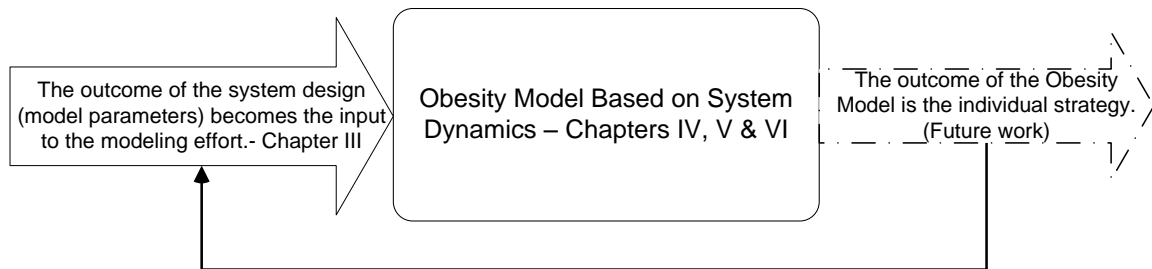


Figure 18 – High Level Diagram

In Figure 18 the structural model of the obesity system is displayed. While initially the model had only a few elements, it evolved in complexity once more elements from the VoC were incorporated. The model includes the elements that were identified

during the system design stage through independent research or after surveying stakeholders, particularly from the general population and healthcare professionals. The structural model presented in Figure 19 was developed through following the same iterative process as the QFD that provided its inputs. Particularly, due to a continuously evolving VoC, establishing the initial baseline in a new system design involves multiple loops by first identifying the VoC elements then clustering and selecting the critical elements. However, the model must have adaptive ability based on any significant change in the needs or wants of the customers, changes in the environment, and progress of technology and other elements critical to the system's existence and performance. In a true sense, it is a dynamic approach to the obesity problem that makes this research unique.





There are three different levels of the model, emerging from an even higher level of the Healthcare Prevention System. In Figure 20 the hierarchical relationship between the levels is presented.

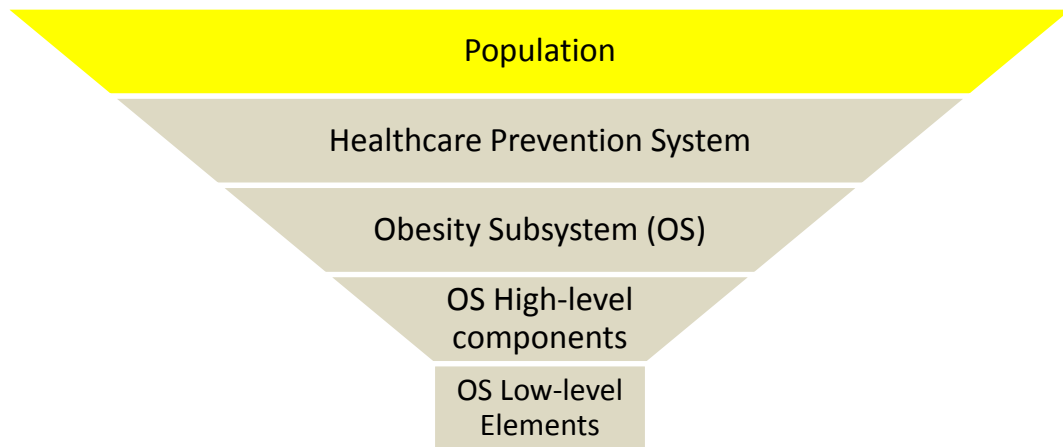


Figure 20 – System Hierarchy

The highest level of the Obesity Subsystem, which emerged directly from the higher level system (Healthcare Prevention), consists of the following components: Individual Characteristics, Non-Physical Factors, Physical Environment, Fitness Activity, Diet, Education and Target Step. They are the result of the system design process, particularly of the QFD. The list was developed based on the current state of knowledge while the grouping or clustering was created based on the inherited or generally acceptable affiliation of structural model elements at different groups. Each of the high level components listed above has lower level elements. For example, the Individual Characteristics cluster contains the elements that are either not under the direct control of the individual (e.g. Age, Height, Family History etc.) or are inherited. It is highly unlikely that the latter subgroup, it is changed, or at least changed easily (e.g. Culture, Family Environment etc.), although are under individual control.

The two outputs of the model can either be Weight Loss increment (when Time is kept constant) or Time to Weight Loss (when Weight Loss is kept constant). The elements of the structural model are discussed below.

In Figure 21, three of the high-level OS components (Individual Characteristics, Non-Physical Factors and the Physical Environment) are illustrated in more detail.

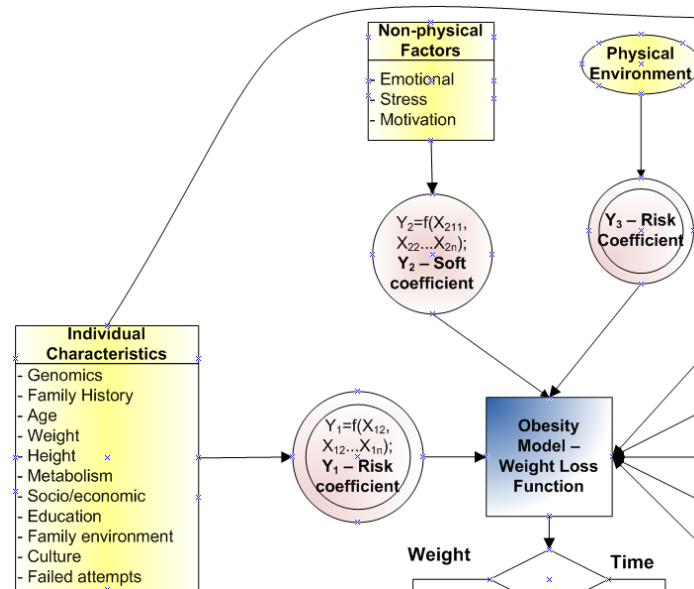


Figure 21 - IC, NPF and PE

- Individual Characteristics (IC) – are endogenous inputs and are either given or measured, resulting in a metric that can be considered constant for the purpose of this model. For example, age is one of the individual characteristics. Age changes continuously but, from the perspective of this work, age can be considered constant. Similarly, height is changing even after the growth of the body is considered zero. Again, for the purpose of this research it can be

considered constant as long as the model is applied to individuals 16 years of age or older. The inputs included in the Individual Characteristics are:

- *Genomics* – This is the collection of information on genetic variation and/or whole genome sequence, where it is intended for risk assessment in disease diagnosis, management and prevention. (Khoury, Feero, & Valdez, 2010). Genomics is a qualitative/descriptive category. It was included since it is a complementary piece of information to the *Family History* that can be used in prevention of diseases. If we know in advance what diseases we are susceptible of contracting throughout our life time, we can probably prepare for or even prevent those conditions from even occurring.
- *Family History (FH)* – It is the collection of information about multiple diseases in relatives. Similarly to genomics, FH is intended for risk assessment in disease diagnosis, management, and prevention (Khoury, Feero, & Valdez, 2010). Also, it is a qualitative/descriptive category. FH has been for many years a very good source of information, attempting to predict future medical conditions based on certain data retrieved from the close family. – (Khoury, Feero, & Valdez, 2010) elaborated on the genetic risk assessment. Both FH and genetic testing in the form of Personal Genomics (PG) have recognized value for the diagnosis and management of rare single gene conditions. However, the balance of benefits and risk factors involved for using them, alone or in combination, as tools for managing risk of common conditions in routine clinical care and disease prevention remains undetermined. It is instructive to compare the evidentiary attributes of FH and PG as personalized tools for risk

assessment and improving health. This is displayed in Table 3. In (Laitinen, Power, & Järvelin, 2001), the authors explain that genetic factors are also related to the development of obesity, as was observed in some studies of twins and adoptees. The likelihood that a child will become obese in adulthood is markedly increased if both parents are obese, if the individual is obese during childhood or adolescence, or if puberty occurs at an early age.

Table 6 - Side by Side Comparison FH vs. PG

Topic	Family History (FH)	Personal Genomics (PG)
Tool	Collection of information about multiple diseases in relatives	Collection of information on genetic variation and/or whole genome sequence
Rationale	Shared genetic susceptibility and environmental factors for common diseases	Genetic susceptibility to common diseases
Intended Use	Risk assessment for disease diagnosis, management, prevention	Risk assessment for disease diagnosis, management, prevention
Methods	Person's recall and/or clinical/ health record linkage	Laboratory assays (genome wide platforms soon may be replaced by sequencing)
Measurement	Should be done throughout life	Done once or infrequently
Price	Inexpensive	Variable but can be expensive for sequencing
Analytic validity (accuracy of measurement)	Variable by disease	Usually high
Clinical validity (association with health outcomes)	Family history established as risk factor for most diseases (depends on number of relatives, age at onset). Has low predictive value.	Genotype–phenotype associations not established for most genetic variants; weak associations for individual variants and has low predictive value
Clinical utility (benefits versus harms)	Not well established for common diseases; useful for rare genetic diseases	Not well established for common diseases; useful for rare genetic diseases

- *Age* – Is the physical age of the individual at the time when the AMHSC is used. The Age is measured in years and is a major element in obesity control.

- *Weight* – Represents the initial weight used in initializing the system, along with other causal relationships as part of the dynamic model. The weight can be measured in either pounds or kilograms. The initial weight of the individual is an important factor in the strategy employed, as well as the alternatives available for weight loss.
- *Height* – Is the current height of the individual measured in either kilograms or pounds.
- *Metabolism* – According to the (Merriam-Webster, 2012)Merriam-Webster Encyclopedia, metabolism is the sum of the processes in the build-up and destruction of protoplasm; specifically the chemical changes in living cells by which energy is provided for vital processes and activities, and the new material is assimilated. Metabolism and its components (Basal Metabolic rate or BMR, Resting Metabolic Rate or RMR, etc.) are measured by specific methods, including an open-circuit, indirect computerized calorimeter equipped with a canopy (Lazzer, et al., 2009). Metabolism is characteristic to each individual. People burn calories at various rates. Two people doing the same activity or even performing no activity at all consume energy at different rates. According to (Martin, et al., 2007), body weight changes are a function of energy balance where weight gain occurs when energy intake exceeds energy expenditure (EE), and weight loss occurs when EE exceeds energy intake. Energy is expended through the resting metabolic rate (RMR), physical activity, and thermal effect of food. The largest component of EE is RMR, which accounts for 60 - 70% of the total daily EE.

- *Socio/Economic* – This represents the position of the individual in society and is a descriptive, rather than quantitative measure. The socio/economic position is one of the determinants for obesity (Craig, Cameron, & Bauman, 2005). Also, (Peters, 2003) argues that obesity is a social problem, driven in many dimensions, mostly by our deeply held values and beliefs, and the systems that we as a society have constructed to develop, reward and perpetuate this value system.
- *Education* – This is the level of education of an individual. It is different from the high-level element Education. While we consider the Individual Characteristic “Education” constant (e.g., high-school diploma, university degree, etc.), the high-level element is a dynamic part of the model that can be controlled by the user since it relates to the obesity specific education. The measure of education level is rather qualitative. An ordinal scale related to the level of understanding of obesity (e.g., low, medium or high) is appropriate.
- *Family Environment* – This component is related to Culture, as well as socio-demographic and lifestyle (Rodearmel, et al., 2006). There is no defined scale for this metric. Consequently, once a decision is made to be introduced into the model, a scale needs to be defined.
- *Culture* – According to the Merriam-Webster dictionary, Culture is the customary beliefs, social forms, and material traits of a racial, religious or social group. Consequently, Culture is one of the elements that is neither easily controllable nor adjustable. There is no metric definition. It is also related with

the Family Environment, as well as lifestyle and socio-demographic (Craig, Cameron, & Bauman, 2005).

- *Failed Attempts* – This is not as evident as the others, and it was described by an obesity specialist that lectures in weight loss classes. Apparently, there is a relationship between the number of times an individual failed and success of the current attempt (as the number of failed attempts increases, there is less chance for a successful and sustainable weight loss strategy). This component needs to be further investigated and confirmed for more clearly identifying the impact on weight loss.
- Non-physical factors (NPF) – These factors are arguably the most difficult not only to quantify but also to control. They will be kept constant initially, although through future research, they need to be considered more as a variable. The three inputs as part of this element include the following:
  - *Emotional* – This plays a major role in an individual's ability for committing to a different approach. As mentioned in (Merriam-Webster, 2012), emotion is a conscious mental reaction (as in anger or fear), subjectively experienced as a strong feeling, usually directed towards a specific object, and typically accompanied by physiological and behavioural changes in the body.
  - *Stress* – According to (Rutters, Nieuwenhuizen, Lemmens, Born, & Westerterp-Plantenga, 2008), several human adult studies in laboratory settings indicate that acute stress may influence energy intake. Acute stress alters food preference, eating frequency, and amount of energy



intake. During stress, food preference is altered towards intake of sweet foods and foods with saturated fats, next to an increase in the intake frequency and amount of food intake. However, not all studies investigating the relationship between energy intake and stress have yielded conclusive results. Stress may also result in an energy intake decrease. This is another input that has a dynamic behaviour as part of the system. A Perceived Stress Scale is proposed by (Cohen, Kamarck, & Mermelstein, 1983), and it can be used for measuring the stress perceived by an individual. A study about the level of impact life and work stress have on obesity is described by (Craig, Cameron, & Bauman, 2005).

- *Motivation* –There is extensive literature that discusses the Motivational Theory and what makes us move forward with an action in our daily lives. There is no measure of Motivation yet to be identified as related to obesity effort.
- Physical Environment (PE) is the place or environment where an individual lives. According to (Craig, Cameron, & Bauman, 2005), the socio-demographic factor is important in obesity control. Living in a downtown core or on a country farm directly influences the way we consider eating.

The purple circles on Figure 21 are the generic causal relationships or transfer functions that actually build the backbone of the model. The notations and forms are generic so they do not have any true meaning.

In Figure 22, three other components of the model are presented in more detail.

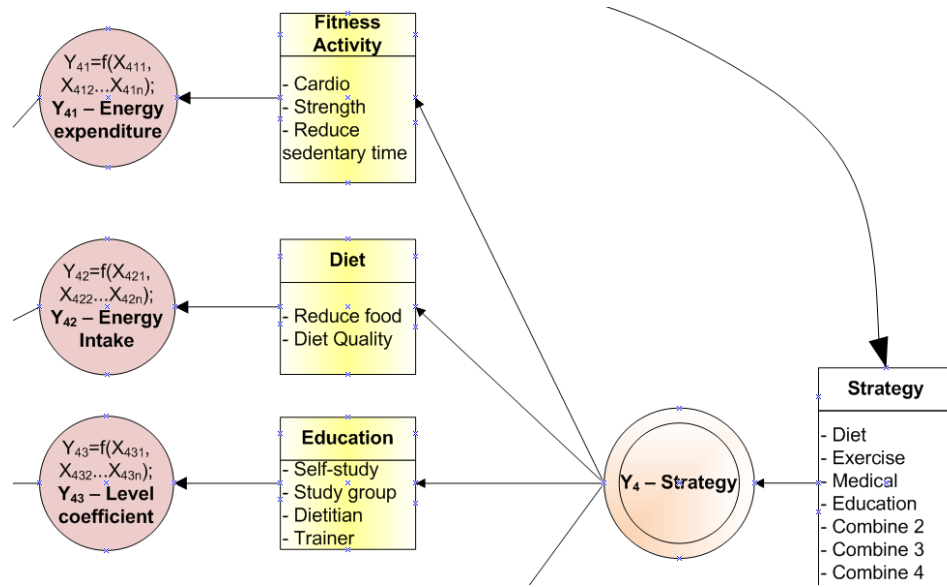


Figure 22 - Fitness Activity, Diet & Education elements

- Fitness Activity – Physical Activity (PA) can be evaluated based on the amount of effort performed by the individual in a 24 hour period. According to (Gerrior, Juan, & Basiotis, 2006) the Physical Activity Level (PAL) provides information about the duration and intensity of a set of different activities performed during a 24-hour period and the relative differences in usual levels of physical activity. The scale used for measuring the PAL is also from (Gerrior, Juan, & Basiotis, 2006) as follows:

$$\Delta PAL = \frac{(METs-1) * \left[ \frac{(1.15)}{0.9} \right] * Duration (minutes)}{\frac{BEE}{[0.0175 * 1440 * weight (kg)]}} \quad (01)$$

Where MET stands for metabolic equivalents (METs), a numerical value that represents a multiple of the resting metabolic rate for a particular activity and BEE is the

basal energy expenditure. After the  $\Delta$  PAL is calculated for each physical activity, the physical activity category (PAL: sedentary, low active, active, or very active) is determined based on the basal activity impact on energy expenditure (a factor of 1.1) and the sum of all activities (sum of  $\Delta$ PAL). This factor accounts for TEF and post-exercise increase in energy expenditure. The PAL is automatically calculated as  $PAL = 1.1 + \text{sum of } \Delta PAL_i$ , where  $\Delta$  PAL<sub>i</sub> is the list of each reported activity impact on energy expenditure.

For men:

- Sedentary: PA = 1.0, when  $1.0 < PAL < 1.4$
- Low active: PA = 1.12, when  $1.4 < PAL < 1.6$
- Active: PA = 1.27, when  $1.6 < PAL < 1.9$
- Very active: PA = 1.54, when  $1.9 < PAL < 2.5$

For women:

- Sedentary: PA = 1.0, when  $1.0 < PAL < 1.4$
- Low active: PA = 1.14, when  $1.4 < PAL < 1.6$
- Active: PA = 1.27, when  $1.6 < PAL < 1.9$
- Very active: PA = 1.45, when  $1.9 < PAL < 2.5$
- *Cardio & Strength* – According to Wikipedia, aerobic exercise and fitness can be contrasted with anaerobic exercise, of which strength training and short-distance running are the most salient examples. The two types of exercise differ by the duration and intensity of muscular contractions involved, as well as by how energy is generated within the muscle. What is

generally called aerobic exercise might be better termed "solely aerobic", because it is designed to be low-intensity.

- *Sedentary time* – Input related to how much time we are not active and not sleeping. According to (Merriam-Webster, 2012), two of the definitions of this term are: “doing or requiring much sitting or “not physically active”
- Diet – Input related to food/drink intake. The main part of the energy balance is the energy that an individual assimilates. Energy Intake can be measured in different units (e.g., calories/time, MJ, etc.). According to (Peters, 2003) for many people, weight gain is the only means to achieve energy balance in an environment that encourages excess energy intake and very low levels of physical activity.
  - *Food* – Source of calories we consume
  - *Diet Quality* – Related to what kind of food we choose to consume

All these components and elements can be in purpose changed over time, resulting in a certain strategy that is meant to take an individual from the current unwanted state to a more desired future state.

The Target Step in Figure 23 is controlled by the individual and it sets the pace for the weight loss. It can be defined as:

- *Weight target* – What is the desired weight?
- *Time target* – What is the desired time to lose a certain weight?

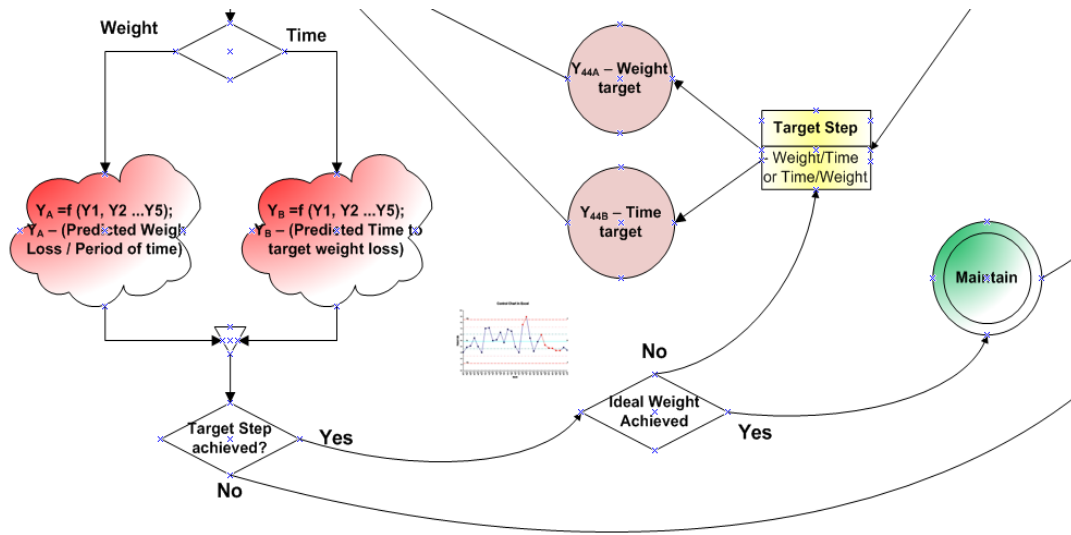


Figure 23 - Target Step, Outcomes and decision points

The two alternative outcomes of the model can be established based on the individual's choice. An individual can choose either the amount of weight that he/she wants to loose over a certain amount of time or, alternately, the amount of time that he/she wants to use in order to lose a certain amount of weight. Again, the causal relationships, as well as the notations are generic and used only for visual representation. The transfer functions are presented and discussed in a subsequent chapter.

The first decision point to consider immediately after the outputs is either for further adjusting the weight if the targets were achieved, or reassess the strategy if the previous alternative was not met.

The second decision point includes directing the user to either set a new Target Step if the final weight was not achieved or, to the “maintenance” mode when the target weight was actually reached. The maintenance mode requires a different strategy that is meant for sustaining the gains and not slipping back to the undesired weight.

(Raine, 2004), introduces the World Health Organization (WHO) guidelines for assessing obesity. In Canada, (Lau, Douketis, Morrison, Hramiak, & Sharma, 2007) published a comprehensive guide to the development of the practice recommendations for fighting obesity, while also acknowledging the breadth of topics to be assessed and the inherent limitations of the obesity literature. The Body Mass Index (BMI) (Ko & Tang, 2007) calculated from weight and height ( $\text{kg/m}^2$ ) is:

$$BMI = \frac{\text{weight in kilograms}}{\text{height in meters}^2} \quad \left[\frac{\text{kg}}{\text{m}^2}\right] \quad (02)$$

and it is used to classify adults as:

- Normal weight (BMI = 18.5 to 24.9  $\text{kg/m}^2$ ),
- Overweight (BMI = 25.0 to 29.9  $\text{kg/m}^2$ ), and Obese (BMI  $\geq 30 \text{ kg/m}^2$ ).

#### 4.2. Obesity System Model - Analytical Approach

The development of the Obesity System Model (OSM) required a sequential approach. The system design methodology is based on building blocks that feed on each other. That is, before the search for solutions there is a need for identifying and analyzing the VoC. That step, in general, is one of the longest in time. The development of the CTS elements cannot be started before the VoC step is completed. This approach continues all the way to solution identification, testing, validation and implementation. Considering what (Box & Draper, 1987) stated, “Essentially, all models are wrong, but some are useful.” In order to become useful, the OSM will start by simulating the basic parts of the system (e.g., behaviors related to personal characteristics, dieting and physical activity

etc.). The model can be further developed through future research to include Education, Physical Environment and Non-physical Factors.

In the first stage of this effort, only a limited number of the parameters identified through system design and used for building the structural model were considered, leading to useful, yet significantly simplified model. In some cases, certain variables were be fixed as constants rather than transfer functions. Some of the parameters excluded during the first iteration of the model building effort need more supporting research (not yet available in literature) to more clearly represent their impact as it relates to obesity. For example, it is recognized that stress is one factor influencing the strategy, and more importantly, the execution of the strategy. However, relatively little has been published to better quantifying this relationship. Similarly, what motivates people to lose weight and sustain their desired level is not clearly understood nor easily quantified in relationship with obesity.

The subsequent chapters present and prove that the first iteration of the model realistically simulates the behaviours related to weight loss within certain boundaries and with acceptable accuracy. The model was calibrated and verified using existing data obtained from real life examples.

A number of equations describing causal relationships have been identified from various sources and were used in the development of the model. An overview of the interrelationships among the publications used in the model development is displayed in Figure 24.

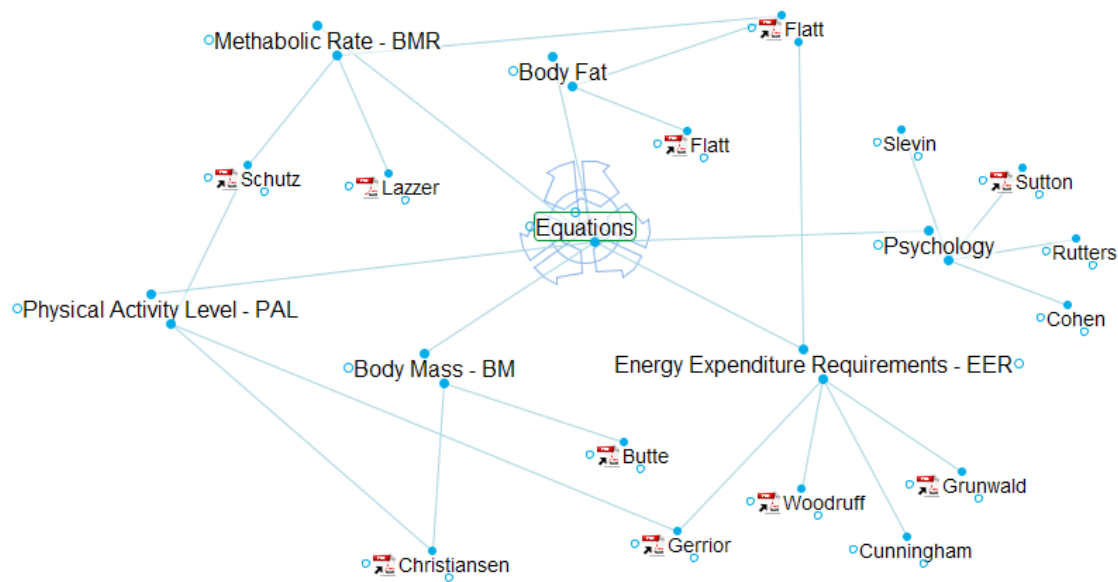


Figure 24 – Causal relationships distribution

In Figure 24, the causal relationships identified as potential candidates for being used in the model development are clustered in several categories including: Body Mass (BM), Physical Activity Level (PAL), Metabolic Rate (BMR), Body Fat, Energy Expenditure Requirements (EER), and Psychology. Under each category, sources and references addressing the respective areas are listed.

One key obstacle is that most relationships are quite complex, involving multiple factors and variables. The papers listed introduce results of numerous experimental studies in support of these relationships. Another challenge obstructing the use of the causal relationships is in identifying a unified way of measuring the variables or properly transforming them to maintain unit consistency throughout the model. As the system development is a sequential process, due to the multiple iterations required to identify and clarify the VoC, not all the causal relationships identified were included in the first iteration described in this work.



A more detailed description of the causal relationships used in the current model follows. All other causal relationships identified and not used are included in the Appendix.

#### 4.3 Key Modeling Causal Relationships

##### Christensen et al

According to (Christiansen, Garby, & Sørensen, 2004), an obesity condition typically develops over time and is reflected in an energy imbalance, leading to a body mass increase too small to be measured or controlled. A mathematical model has been defined for describing the relation between the change in body mass, values of the energy intake (*EI*) and the energy expenditure (*EE*), controlled by the physical activity factor (*PAF*).

A general view of the energy balance is presented in Figure 25. The two major elements associated with the energy intake are Food and Drink consumption. On the other side, the main two elements associated with energy expenditure are Physical Activity and Basal Metabolic rate. However, an additional element is introduced in the model based on relatively recent research in the field. That is the energy consumed to transform food in either fat or lean tissue. While not as impactful as the other two elements, it can be up to 20% of the overall contribution. Although not introduced in the model at this point, the Energy Loss due to temperature variations is also a factor to be considered in the overall balance.

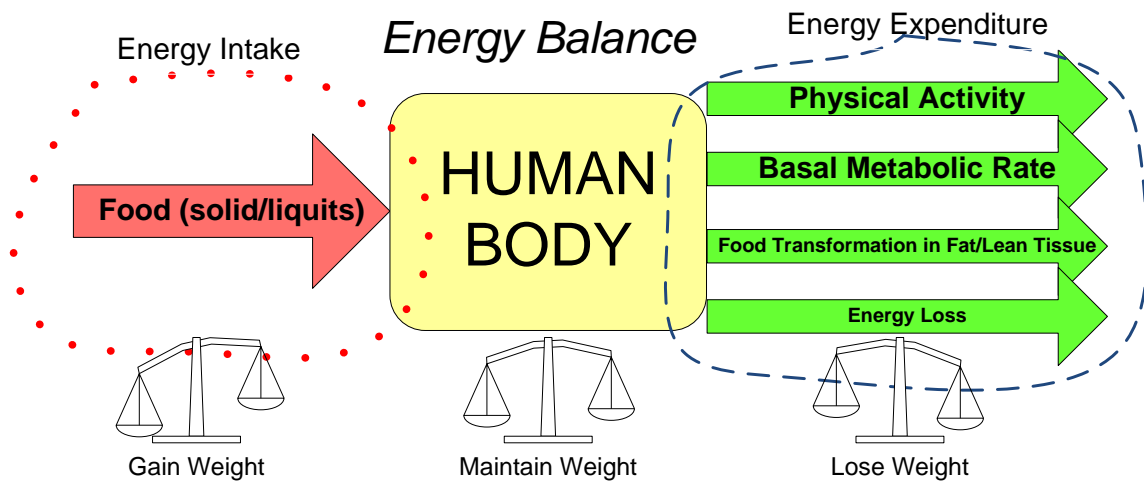


Figure 25 – Energy Balance

In Figure 25, the scales represent the three conditions the human body can be at any point in time. On the left hand side, if the energy in-taken is more than expended, the individual gains weight. Alternately, if the direction is reversed as shown on the right hand side scale, the individual is losing weight. The balance is achieved when the two are equal.

The components of energy expenditure that are not due to the PAF increase with the body mass increase include: the energy expenditure of a larger mass and energy expenditure necessary to convert matter into tissue. Both contributions depend on the fraction of fat in the added tissue. Based on data from the literature, the fraction of fat in the additional tissue and energy required to convert energy into tissue are estimated and included in the model.

Energy-based theoretical relations between the various factors involved in energy balance help in identifying and quantifying the components for balance and understanding their relations during development of an obesity condition. The inclusion

of increased energy expenditure to convert food energy to tissue changes the previous estimates of the energy imbalance by about 20 percent.

The steady-state (or the equilibrium solution) can be written as follows:

$$\frac{EI}{PAF} = BMR(BM_{ss}) = BMR_0 + (k_f f_r + k_l(1 - f_r)) \times (BM_{ss} - BM_0) \quad (03)$$

Steady-state body mass only depends on  $BMR_0$  and the ratio of  $EI/PAF$ :

$$\frac{\Delta BM_{ss}}{\Delta \frac{EI}{PAF}} = \frac{1}{k_f f_r + k_l(1 - f_r)} \quad (04)$$

In the present model, the ratio between change in  $EI/PAF$  and change in  $BM_{ss}$  depends only on  $f_r$ ,  $k_f$  and  $k_l$ , of which only  $f_r$  may be dependent on the between-subject variation.

The general equation for the development of body mass in time includes:

$$\frac{dBM}{dt} = \frac{EI - PAF(BMR_0 + (k_f f_r + k_l(1 - f_r))(BM - BM_0))}{\frac{c_f f_r}{e_f} + c_f(1 - f_r)/e_l} \quad [\text{kg/day}] \quad (05)$$

The efficiency in converting surplus energy into new tissue has no influence on steady state, but has a direct proportional influence on the rate of weight increase during periods of positive energy imbalance.

Nomenclature:

- $BM_0$  – reference body mass [kg]
- $BMR_0$  – basal metabolic rate at  $BM_0$  [MJ/d]
- $BMR$  – basal metabolic rate [MJ/d]
- $TEE$  – total energy expenditure [MJ/d], not including  $EEc$  below
- $PAF$  – physical activity factor, defined as  $TEE/BMR$

- $EI$  – energy intake [MJ/d]
- $EI_{ss}$  – steady-state energy intake for given body mass and  $PAF$
- $EEc$  – energy expenditure used to convert excess energy into tissue
- $C$  – total content of combustible energy in the body [MJ]
- $BM$  – body mass [kg]
- $BM_{ss}$  – steady-state body mass for constant  $EI$  and  $PAF$
- $FM$  – fat mass [kg]
- $LM$  – lean mass [kg]
- $f_r$  – fraction of fat in new tissue ( $= \frac{\Delta FM}{\Delta BM}$ )
- $c_f; c_l$  – energy stored per kg fat, respective lean, tissue [MJ/kg]
- $k_f; k_l$  – basal metabolic rate per kg fat, respective lean tissue [MJ/(kg\*day)]
- $e; e_f; e_l$  – efficiency in the conversion of energy to new tissue

The combustion energy of fat  $c_f$  and lean tissue  $c_l$  were taken from (Garrow, 1978). The energy expenditure of fat  $k_f$  and lean tissue  $k_l$  were taken from (Garby, et al., 1988). The values are:

$$c_f = 30.0 \text{ MJ/kg}, \quad c_l = 4.0 \text{ MJ/kg}, \quad k_f = 0.027, \quad k_l = 0.116 \text{ MJ/(kg*d)}$$

The fraction of fat,

$$f_r = \frac{\Delta FM}{\Delta BM} \quad (06)$$

in added tissue during weight increase has been examined in several papers including: Heitman and Garby (Heitmann & Garby, 1998) and (Heitmann & Garby, 2002). It was observed that  $f_r$  was constant and independent of body weight over a wide range, with

$f_r = 0.67$  for men and  $f_r = 0.76$  for women. These values will be used in the remainder of this work.

The fraction of fat mass in the body taken from (Heitmann & Garby, 1998) corresponds to the following values of  $BMR_0$ , which are used in the computations in the proposed model:

$$\text{Men: } BMR_0 = 7.8 \text{ MJ/d} \quad \text{and} \quad \text{Women: } BMR_0 = 6.8 \text{ MJ/d}$$

(Noblet, Karege, Dubois, & van Milgen, 1999) calculated the efficiencies  $e_f$  and  $e_l$  separately, using five different statistical methods for handling their data. The values used in this paper include:  $e_f = 0.85$  and  $e_l = 0.55$ .

The causal relationships (03) through (06) can be considered in several different ways such as:

a) First, compute the change in steady-state body weight caused by a change in energy intake or physical activity factor. Consider a person in a steady state who instantaneously changes the values of  $EI$  and/or  $PAF$  to new values, which are subsequently maintained as constant. The body weight will approach a new steady state, and the difference between the old and new steady state can be computed.

Using the constant values from the previous section, Equation (04) gives:

$$\frac{\Delta BM_{ss}}{\Delta \frac{EI}{PAF}} = \begin{cases} 17.7 & (men) \\ 20.7 & (women) \end{cases} \frac{kg}{MJ/d} \quad (07)$$

If for example, the ratio  $EI/PAF$  is increased in a steady state situation by 0.1 MJ/d and kept constant thereafter, the resulting increase in steady-state body weight is 1.77 kg for men and 2.07 kg for women per year.

b) If an asymptotic approach to steady state is taken then the case can be considered where  $EI$  and  $PAF$  are constant while  $BM_{ss}$  is generated from Equation (04). Assume that the present body weight  $BM(0)$  is not in steady state, as a result from a previous change in life style. Equation (03) may then be used to eliminate  $BMR_0$  from Equation (05). The result is Equation (08):

$$\frac{dBM(t)}{dt} = PAF \frac{k_f f_r + k_l(1-f_r)}{\frac{c_f f_r}{e_f} + c_l(1-f_r)/e_l} \times (BM_{ss} - BM(t)) \quad (08)$$

If  $f_r$  is independent of body mass, the solution  $BM(t)$  to Equation (09) is a simple exponential asymptotic increase towards the new steady state body mass. The solution becomes:

$$BM(t) = BM_{ss} - (BM_{ss} - BM(0)) \times e^{-PAF \frac{k_f f_r + k_l(1-f_r)}{\frac{c_f f_r}{e_f} + c_l(1-f_r)/e_l} t} \quad (09)$$

The solution does not depend explicitly on  $EI$  or  $BMR_0$ , but only implicitly through  $BM_{ss}$ . The half-time ( $T_{1/2}$ ) for this asymptotic approach (i.e., the time it takes before  $BM(t)$  has changed by half of the difference  $BM_{ss} - BM(0)$ ) is generated by the expression:

$$T_{1/2} = \frac{\ln 2}{PAF} \frac{\frac{c_f f_r}{e_f} + c_l(1-f_r)/e_l}{k_f f_r + k_l(1-f_r)} = \begin{cases} \frac{320}{PAF} & \text{days (men)} \\ \frac{409}{PAF} & \text{days (women)} \end{cases} \quad (10)$$

c) Subsequently based on the observations in Heitmann and Garby (Heitmann & Garby, 1999), the situation with a constant rate of increase in body weight can be considered. From Equation (04), the time course of  $EI$  is computed, assuming a constant value for  $PAF$ , in order to achieve a constant value for  $dB M(t)/dt$ . The computed value of

$EI(t)$  is compared with the value  $EI_{ss}$  that corresponds to a steady state situation with the present value of  $BM$  and  $PAF$ , and  $EI_{ss}$  is computed from Equation (03). An interesting feature is that the energy intake exceeds the steady-state value by only a very small amount. Therefore, efforts can be focused on the difference  $EI - EI_{ss}$ :

$$EI - EI_{ss} = \left( \frac{c_f f_r}{e_f} + \frac{c_l(1-f_r)}{e_l} \right) \frac{dBM}{dt} \quad (11)$$

This difference is independent of  $BM$  and proportional to the rate of weight increase.

In the analysis above, it is assumed that the activity factor  $PAF$  is constant, thus the weight increase is caused by excess energy intake alone. The analogous analysis can be performed for constant energy intake  $EI$ , assuming that the weight increase is caused exclusively by inadequate physical activity. For the difference, it can be noted that:

$$PAF_{ss} - PAF = \frac{dBM}{dt} \times \frac{\frac{c_f f_r}{e_f} + c_l(1-f_r)/e_l}{BMR_0 + (k_f f_r + k_l(1-f_r))(BM - BM_0)} \quad (12)$$

And for the relative difference (dimensionless):

$$\frac{PAF_{ss} - PAF}{PAF_{ss}} = \frac{dBM}{dt} \frac{\frac{c_f f_r}{e_f} + c_l(1-f_r)/e_l}{EI} \quad (13)$$

that is independent of body weight.

### Lazzer

According to (Lazzer, et al., 2009), a simple energy balance model based on BW, Age and Gender is as accurate as more complex models based on body composition.

BMR has frequently been the main focus of attention in the studies on the development and treatment of obesity. It can be considered as the sum of the EEs of tissues and organs in a fasting and resting state, and in thermoneutral conditions. It depends on the mass and metabolic rate of tissues and organs. For instance, EE is ~10, 15, 20, 35, and 35 times higher in the digestive tract, liver, brain, heart, and kidney, respectively, than in resting muscle, whereas EE is only ~1/3 the value of resting muscle in white adipose tissues. Thus, although organs only account for ~7% of BW, they contribute ~60% of BMR. Figure 26 illustrates the proportions of EE among different body organs/functions.

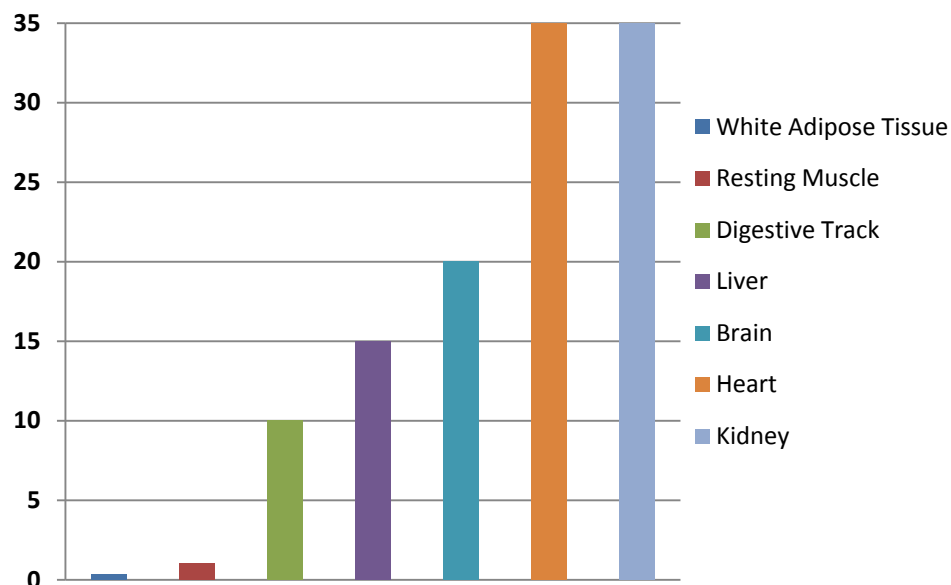


Figure 26 – Proportions of EE for Various Organs/Functions

In comparison, skeletal and adipose tissues account for 35–40% of BW but only 18–22% and 3–4% of BMR, respectively. Generally, BMR depends on body composition as expressed by fat-free mass (FFM), fat mass (FM), and on gender, age, physical activity



and nutritional status. The main determinant of BMR is FFM, whereas FM is significant only in obese subjects. Gender is also a significant determinant of BMR, with men having a greater BMR than females after adjustment for body composition. That means that, the men use more energy than women to keep the body functional which explains why, if everything else is kept the same, men lose weight at a faster rate than females. In addition, BMR markedly decreases with advancing age in sedentary populations at a rate of ~1–2% per decade after the age of 20. Such a decline in EE probably contributes to an impaired ability to regulate energy balance with age. Several studies have addressed the issue of whether EE decreases with age, and whether females have lower EE than males, but the literature is equivocal on this topic concerning obese subjects. This aspect needs to be clarified better in the future in order to be able to properly quantify the EE. According to (Gallagher, Aaron, Wang, Heymsfield, & Krasnow, 2000) as an example, factors other than organ atrophy may contribute to the lower metabolic rate of older persons. Additional studies are required to investigate whether there is a reduction in the oxidative capacity of individual organs and tissues.

The aim of Lazzer's study was to derive the relationship between BMR, gender, age, anthropometric characteristics and body composition in a very large sample of severely obese white subjects. Four different models were developed with increasing complexity levels by using a higher number of predictors. They all had the same prediction power between 55 and 62%. Thus, a simple model based on BW, age and gender is as accurate as more complex models based on body composition.

Therefore, the simplest causal relationships for the prediction of BMR in adults are used and include the following:

$$BMR = 46 \times BW - 14 \times Age + 1,140 \times gender + 3,252 \quad (14)$$

### Butte

(Butte, Christiansen, & Sørensen, 2007) developed an energy balance model based on empirical data and human energetics to predict the total energy cost of weight gain and obligatory increase in energy intake and/or decrease in physical activity level associated with weight gain in children and adolescents.

They assume that BMR is calculated by the expression:

$$BMR = kf \times FM + kff \times FFM \quad (15)$$

The authors argue that in (Christiansen, Garby, & Sørensen, 2004), the basal EE of FM (kf) and basal EE of FFM (kff) were assumed to be constants common to all adults. However, this data makes it possible and necessary to estimate values for each sex and Tanner stage group. Tanner scale or stage as a scale measures the physical development of children, adolescents and adults. In the literature, the physical activity level (PAL) has frequently been defined as the ratio between total EE and basal metabolic rate:  $PAL = TEE/BMR$ . However, some part of the EE does not depend on physical activity. Therefore, a more complex equation is used for total EE during weight gain, accounting for conversion energy (CE) and diet-induced EE (DIEE). CE is the energy used to convert dietary energy intake into combustible energy in new tissue. They assume that  $DIEE = 0.1 EI$ . In (Christiansen, Garby, & Sørensen, 2004), this term was ignored, with the argument that it can be included in the definition of EI (replace EI by 0.9 EI). This is not adequate when the estimation of energy requirements is a key issue.

$$TEE = CE + DIEE + PAL \times BMR \quad (16)$$

The efficiency of the conversion from EI into new tissue depends on the composition of the tissue. The authors model this effect by the two efficiency coefficients  $ef$  (efficiency in the conversion of energy to FM) (0.85) and  $eff$  (efficiency in the conversion of energy to FFM) (0.42) for the formation of FM and FFM, respectively. If  $fr$  denotes the fat fraction in new tissue, this is partitioned as:

$$\Delta FM = fr \times \Delta BM, \Delta FFM = (1 - fr) \times \Delta BM \quad (17)$$

The following relationship between energy imbalance and rate of increase in body mass (BM) is derived in the adult model:

$$\frac{dBM}{dt} = \frac{1}{c} (0.9 \times EI - PAL \times BMR) \quad (18)$$

Where the constant  $c$  is generated by:

$$c = cf \times \frac{fr}{ef} + cff \times (1 - fr) \div eff \quad (19)$$

Energy stored per kilogram of FFM ( $cff$ ) equals 4.48 kJ/g (1.07 kcal/g) based on the assumptions that FFM is comprised of 0.19 g protein/g FFM on average, and the heat of combustion of protein is equal to 5.65 kcal/g. Energy stored per kilogram of FM ( $cf$ ) equals 9.25 kcal/g based on the heat of combustion of fat;  $eff$  equals 42% for protein and  $ef$  equals 85% for fat.

#### 4.4 Issues and Misconceptions about Obesity

For the more advanced, future stages of this research, in order to accurately model the human body, previously identified issues/misconceptions need to be considered. At a

minimum, even if solutions are not available for some of the concerns, at least the boundaries and the constraint of the model can be properly identified.

This thesis supports the fact that an evidence based approach should be sought in order to accurately model the obesity problem. A common sense approach is insufficient, although used extensively and maybe even effectively on occasion. The research for this dissertation promotes an evidence based decision making methodology, starting from the very beginning of the system design phase, and building on a data driven approach for the development of the final model.

(Flatt J. , 2011) discusses several issues and misconceptions related to obesity. A summary list of such issues mentioned in his report is presented below. For detailed explanations, please see the original paper.

1. For problems in applying the energy balance concept, the model must directly support in clarifying the influences and extent of the strategy for the weight loss. For example, the model can differentiate between the progress made when a strategy based on diet is used versus one based on physical activity. The individuals have choices based on their own body and needs.

2. Problems with the metabolic efficiency concept. For the misleading emphasis on the importance of low resting metabolic rates, the model allows for verification of different outcomes based on varying these rates. The difference between individuals can be assessed.

4. There are misleading expectations about the importance of adaptive thermogenesis that represent the decrease in energy expenditure (EE), beyond what could be predicted from the changes in fat mass or fat-free mass, under conditions of

standardized physical activity, in response to a decrease in energy intake (Major, Doucet, Trayhurn, Astrup, & Tremblay, 2007). This means that the human body has the capacity to compensate, at least partly, for the prescribed energy deficit, possibly going beyond any good compliance of some patients. The model developed by this thesis will be able to simulate such scenarios and identify when the decrease in weight is not achieved at the level expected, either due to adaptive thermogenesis or other causes.

5. Problem in judging the importance of de novo lipogenesis and its metabolic cost.

6. Failure to recognize the greater impact of energy intake than expenditure. This can be readily proven by the proposed model. If everything is kept constant, the impact of an aggressive strategy based on only physical activity, where the diet does not change, is lower than the impact of an aggressive strategy based on diet only when the physical activity factor is kept constant. Furthermore, the model can simulate the combination for both which can be shown as an improved strategy compared to the individual approaches.

7. Conditions for body weight stability can compare settling point versus set point. This is another concept that can be identified by using the model. If the settling point is reached, irrespective of the set point, there will be no change or at least not significant enough one even if the strategy is followed. The model will show a flat area when the change in weight is not occurring, so the settling point can be identified. That is also due to the change in BMR based on the change in weight, as well as age that can also be simulated.

8. There are challenges between food intake regulation and carbohydrate balance. It is anticipated that in the future development of this model, the depth of the simulation

will reach to the level of accounting for not only the type of food but also chemical composition.

9. There is confusion about the leverage of exercise on body weight. This observation is very much related to the seventh point in the list. The full advantage of exercising is achieved in combination with a dieting strategy. The leverage of the exercise on body weight is, in researcher's opinion, one of the most misunderstood factors and probably causing as much harm as good in a weight loss plan.

10. How can inherited traits influence body weight regulation? The model will be capable in the future to provide insight related to family history and its influence to weight loss strategy.

## CHAPTER V

### MODEL DESCRIPTION AND OPERATIONS

#### 5.1. Building the Case for Systems Dynamics

(Hammond, 2009) argues that the complexity of the systems underlying the obesity epidemic has important implications for the scientific study of obesity, policy and design of interventions aimed at changing the course of the obesity epidemic, and modeling. He also notes that among other ways of modeling obesity, the Systems Dynamics (SD) technique is particularly effective at providing insight into large systems having good existing data for most relationships between aggregate variables. This makes the sensitivity analysis very straightforward to facilitate both of these goals (i.e. changing the course of obesity evolution and modeling the human body).

Within the introductory section of (Sterman, 2000), many of the author's claims can be directly applied to both healthcare and obesity systems, although they are made towards either a more general system perspective or are business related. The author mentions that the greatest constant of modern times is change, and more importantly, most of the changes for which there now is a struggle to comprehend, arise as either intended or unintended consequences of humanity itself. All too often, well-intentioned efforts to solve pressing problems lead to policy resistance, where policies are delayed, diluted or defeated by the unforeseen and sometimes uneducated responses of other people or nature. By extrapolating the above statements to healthcare issues, it can be observed that improvements in the medical technology, research, medical aids, etc. may actually lead to desired goals such as increasing the human longevity and quality of life. One consequence that was not anticipated was the relative increase in the cost of

healthcare due to the considerably longer life of the individuals, especially in industrialized societies.

Along the same lines, there was a natural progress of the humankind towards producing cheaper, more affordable, richer foods with the intention of eliminating or reducing hunger and malnutrition. This led to an unintended consequence of a growing increase in obesity, with many other related detrimental problems emerging, ultimately making the world even more complex.

According to (Sterman, 2000), SD is a method to enhance learning in complex systems. SD is fundamentally multidisciplinary. Because of the concern for the behaviour of complex systems, SD is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics and engineering. When these tools are applied to the behaviour of humans, as well as the physical and technical systems, system dynamics draws on cognitive and social psychology, economics, and other social sciences.

The use of SD as the modeling philosophy for the obesity system is justified. The human body, not the least from the obesity perspective, most definitely can be categorized as a complex system. Moreover, the obesity pandemic is not a physical consequence nor can it be solved by only dieting or physical activity. A multidisciplinary approach needs to be employed in order to simultaneously address the psychological aspects of weight gain or loss, as well as to deal with the economic and social consequences.

Another striking parallel between SD and its use for modeling healthcare systems is related to the unanticipated side effects of our actions. (Sterman, 2000) claims that it



has been acknowledged for a long period of time that people seeking to solve a problem often make it worse. Developed policies may create unanticipated side effects. Any attempts to stabilize a system may destabilize it. Some decisions may provoke reactions by others seeking to restore the balance after the system was upset. Forrester (1971a) classifies such phenomena as “counterintuitive behaviour of social systems.” These unexpected dynamics often lead to policy resistance and a tendency for delayed intervention, often leading to a diluted or defeated system response to the intervention itself (Meadows, 2008).

Any model has limits in any case and no matter what we do. That is partially due to the missing factors that are not accounted for and also due to the inaccuracies of creating the links and understand fully the loops of the system. However, as mentioned by Meadows, oftentimes the behaviour of the systems is counterintuitive, which means that using the intuition would provide a completely wrong solution. The alternative is to use modeling and, from that perspective, systems dynamics concepts provide the ability to look at the systems from a higher perspective so the interactions between factors can be accounted for as well as the nonlinearity of their behaviour.

At a very high level, Table 7 connects the four pillars of SD to the subject of this research including: prevention/obesity system development and modeling.

This explains some of the difficulties faced in the efforts to control obesity. Due to its complexity, the policies created at the population level, as well as self-created at the individual level, often times create unintended consequences. For example, encouraging competition based on product cost was the intended approach for providing affordable living to all individuals. However, the unintended consequence was the flood of cheap

fast-food products that were unhealthy and artificially developed. This encouraged the consumption of fattening foods, leading to an increase in the quantity of food consumed and decrease in food quality. Also at a personal level, due to an insufficient understanding for self-induced weight control or following the myriads of dieting recipes, the food restriction often led to a quick regain of the weight lost and the addition of more. Obesity is a complex problem and needs to be acknowledged, accordingly.

Table 7 – SD versus Prevention/Obesity System

<b>Systems Dynamics</b>	<b>Prevention/Obesity System Development &amp; Modeling</b>
Accumulation matter (flows & stocks)	The fundamental balancing equation related to obesity is a function of flows (or Energy Intake/Expenditure) and stocks (Human Body).
Feedback (circular causality)	There is a clear feedback loop related to the amount of energy received and energy expenditure that cause certain behaviour of the human body.
Nonlinearity	The variables related to obesity behave in a nonlinear fashion.
Uncertainty	The human body does not behave only in a deterministic way but also in a stochastic mode. This means there is always uncertainty in predicting the outcome of a weight loss strategy.

As a conclusion to the above arguments, by using a SD approach will allow researchers to account for the interactions between different elements of the obesity system, as well as the non-linearity and complexity of the human body and behaviour.

## 5.2. Systems Dynamics Modeling Environment

The vocabulary of SD is rather extensive and oftentimes specialized. Several of the most important terms described in (Sterman, 2000) are listed below as short definitions:

- Stocks & Flows – the concept of stocks and flows is a central idea in dynamic systems theory. Stocks are accumulations. They characterize the state of the system and generate information upon which decisions and actions are based. Stocks give systems inertia and provide them with memory. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. By decoupling rates of flow, stocks are the source of disequilibrium dynamics in the systems.
- Causal Loop Diagrams – are important tools for representing the feedback of the structure of the systems. They capture hypotheses about the causes of dynamics, as well as elicit and capture the mental models of individuals or teams by communicating the important feedbacks believed to be responsible for a problem.
- Delay – is a process with an output that lags behind its input in some fashion. It takes time to measure and report information since it takes time to make decisions. It also takes time for decisions to affect the state of the system. It is critical to understand how the delays behave, how to represent them, how to choose among various types of delays in any modeling situation, and how to estimate their duration. The delays can be material delays that capture the physical flow of material, or information delays that represent the gradual

adjustment of perceptions or beliefs. In general, any belief or perception involves an information delay because humans cannot instantaneously update their mental models as new information is received.

(Stermann, 2000)'s steps of the modeling process are listed below. The presented work uses these steps as a baseline, and references are made throughout this dissertation.

#### 1. Problem Articulation (Boundary Selection)

- Theme selection: What is the problem? Why is it a problem? – This was addressed in the Introduction chapter.
- Key variables: What are the key variables and concepts to be considered? – Developed based on the VoC through QFD, and the design methodology proposed in Chapter III of this work.
- Time horizon: How far in the future should we consider? How far back in the past was the problem first defined? – While this research is meant to be long term (5-10 years), the approach will be incremental. This means that the first stage will end with the development of a limited model, and will simulate within a certain accuracy and given conditions of the human body. The next levels of this work will build on this stage and increase the usefulness, as well as generality of the model.
- Dynamic problem definition (reference modes): What is the historical behavior of the key concepts and variables? What might be their behavior in the future? – There are several categories of variables identified by the system design approach. The first category is very well researched and the information is readily available (e.g., Energy Intake, Physical Activity, Basal Metabolic Rate

etc.). In addition, this model will not only relate the combination of the effects for multiple variables but also the interactions between such variables. The second category includes variables that are well researched, and they will be introduced sequentially in the future developments of this model.

## 2. Formulation of Dynamic Hypothesis

- Initial hypothesis generation: What are the current theories of the problematic behavior? – A summary of the current situation for the obesity pandemic is presented in the Introduction chapter. The problematic behavior consists of the efforts expended for eliminating or reducing obesity but that are not providing the expected outcomes.
- Endogenous focus: Formulate a dynamic hypothesis that explains the dynamics as endogenous consequences of the feedback structure. This stage is introduced in Chapters IV and V of this work for the development of the prevention/obesity system/subsystem, as well as the employment of SD to support a sustainable solution.
- Mapping: develop maps with a causal structure base on the initial hypotheses, key variables, reference modes, and other available data, using tools such as:
  - Model boundary diagrams
  - Subsystem diagrams
  - Causal loop diagrams
  - Stock and flow maps
  - Policy structure diagrams

Chapter IV & V address this point.

### 3. Formulation of a Simulation Model – Chapter V

- Specification of structure, decision rules
- Estimation of parameters, behavioral relationships and initial conditions
- Tests for consistency with purpose and boundary

### 4. Testing – Chapter VI

- Comparison to reference modes: Does the model reproduce the problem behavior adequately for the purpose?
- Robustness under extreme conditions: Does the model behave realistically when stressed by extreme conditions?
- Sensitivity: How does the model behave given uncertainty in parameters, initial conditions, model boundary and aggregation?
- Other tests

### 5. Policy Design and Evaluation – To be addressed by future research

- Scenario specification: What environmental conditions might arise?
- Policy design: What new decision rules, strategies and structures might be attempted in the real world? How can they be represented in the model?

### 6. “What if...” analysis: What are the effects of the policies? – Chapter VI

### 7. Sensitivity analysis: How robust are the policy recommendations under different scenarios and given uncertainties? – Chapter VI

### 8. Interactions of policies: Do the policies interact? Are there synergies or compensatory responses? – To be addressed by future research.

The software used for building the model is VENSIM (Surhone, Tennoe, & Henssonow, 2010). Typically, it is used to assist enterprises in finding an optimal

solution for various situations requiring analysis, where all possible results of future implementation or decisions when developing causal relationship models must be evaluated.

Before choosing VENSIM as the dynamic modeling software, several other options were considered and compared (e.g., Consideo, Dynamo, Sphinx SD Tools, Stella, iThink, etc.). For model building, VENSIM and other system dynamics languages have a great deal in common, with similar functions and default graphical presentations. A summary of the software available is presented in Table 2.

### 5.3. Model Structure and Description

Figure 27 provides an overview for a prototype of the obesity system model.

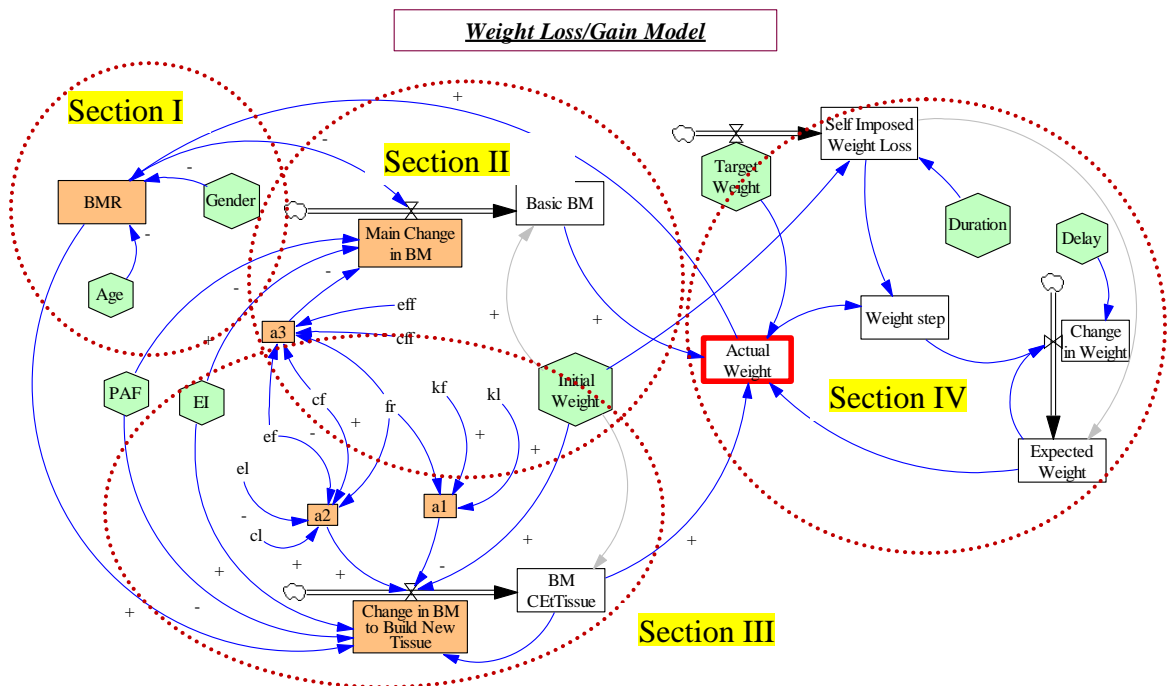


Figure 27 - Obesity System model

There are four distinct sections of the model. The first three correspond to the causal relationships identified in the previous chapters. The fourth section is the engine for the entire model that manages the infrastructure of the simulation.

Section I includes Lazzer's equation (Lazzer, et al., 2009) for calculating the BMR as the main driver. The inputs to this function are Age and Gender. It is readily identifiable that BMR becomes an input in turn to both of the adjacent main functions that include: Main Change in Body Mass (BM) and Change in BM to Build New Tissue. The structure of Section I is presented in Figure 28. BMR incorporates Gender, Age and Actual Weight as inputs.

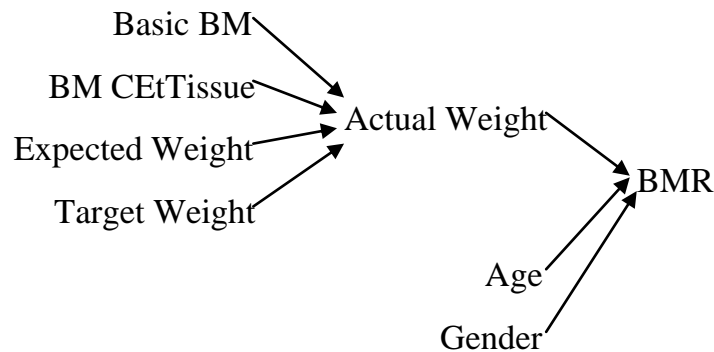


Figure 28 – Section I Structure

Section II is dominated by Butte's transfer function (Butte, Christiansen, & Sørensen, 2007) for introducing Main Change in Body Mass. There are three main inputs to this function that consist of: BMR, Physical Activity Factor and Energy Intake. The  $a_3$  coefficient is also an input to this transfer function, as introduced in the previous chapter. It can be observed that elements of the  $a_3$  coefficient are shared by the main function in Sections II and III. The Basic BM is in fact a result of the change in weight due to the Main Change in Body Mass. The structure of this section is displayed in Figure 29.



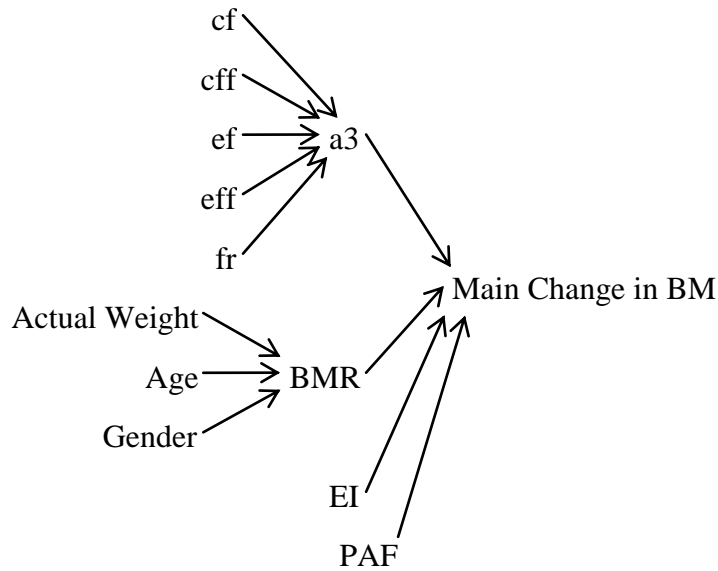


Figure 29 – Section II Structure

In Section III, the transfer function developed by (Christiansen, Garby, & Sørensen, 2004) - Change in BM to Build New Tissue - has the same control structure as the Main Change in BM. This means that the change in body mass related to the energy used for transforming the food in either fat or lean tissues is quantified through a differential equation. Once again, there are several common inputs that are similar to the Basic BM transfer function. Adjacent to EI, PAF and BMR, there are two coefficients –  $a_1$  and  $a_2$  – generated by several constants as identified in (Christiansen, Garby, & Sørensen, 2004). The complete structure is presented in Figure 30.

Section IV represents the user's strategy to the overall weight loss plan. The user defines the goal for the weight loss. In addition, they can adjust the duration of the weight loss period, based on how much time they expect to spend until they achieve the goal. The model also has some safety features incorporated into Section IV.

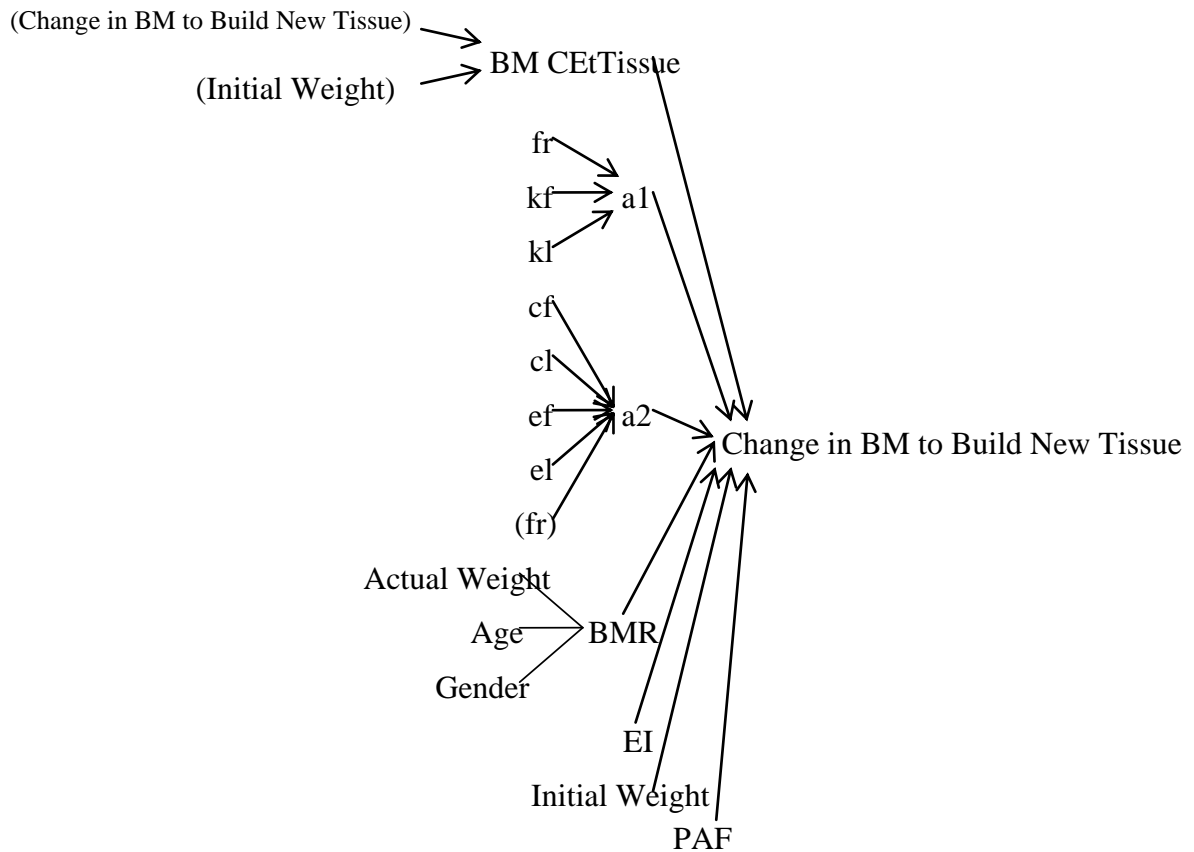


Figure 30 – Section III Structure

The first safety feature is the continuous check on the progress of the weight loss plan. If the actual weight at a certain point is less than the one planned by the individual, the actual weight is used as the reference for the next step. However, if the planned weight is less than the actual weight – meaning that the individual did not achieve the intermediate goal – then the previous goal is used again as the reference. This happens until the individual is actually achieving the intermediate target.

Another safety feature incorporated in the model, particularly in Section IV, is the prevention for the progress of the weight loss strategy beyond the goal established at the beginning. This means that an individual cannot lose weight beyond what was initially

planned without personally adjusting the goal. If this happens, the model will keep the weight constant at the target initially achieved. The structure of Section IV is presented in Figure 31.

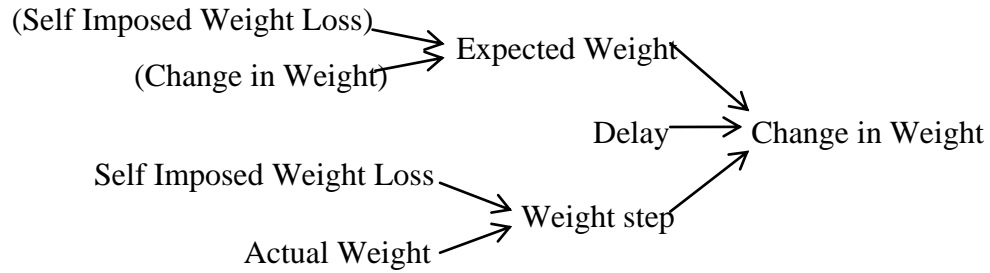


Figure 31 – Section IV Structure

The relationship between the elements of the model is presented in Figure 32.

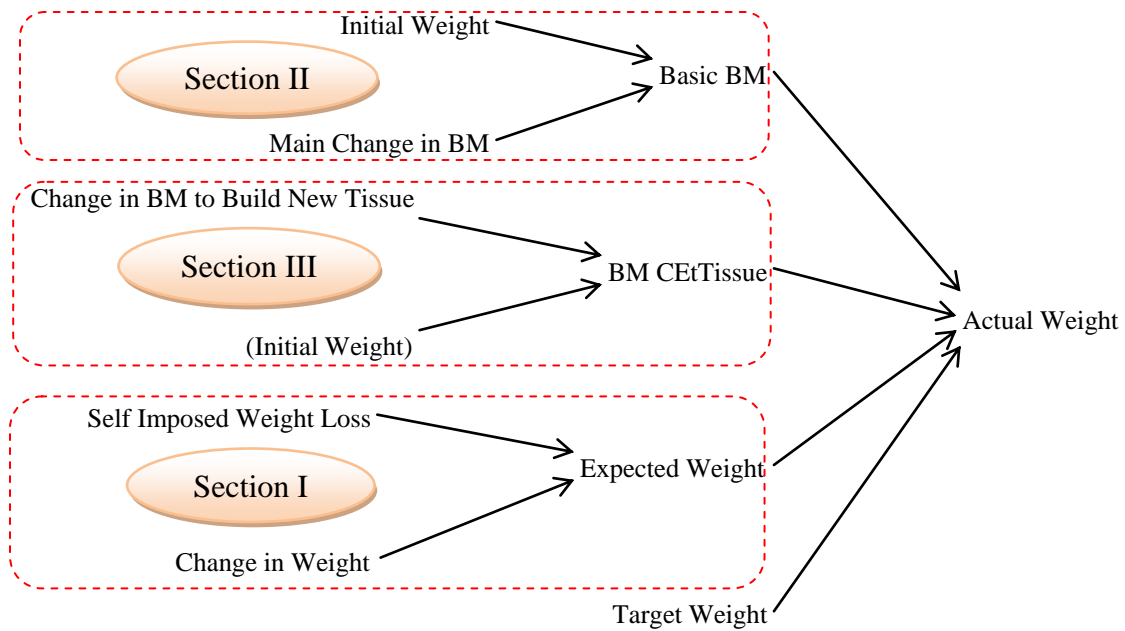


Figure 32 –Model Infrastructure

The diagram presented in Figure 32 is intended for making the overall structure of the model transparent. The four main transfer functions or pieces of information that are

combined result in the Actual Weight and include: Basic BM and BM CEtTissue. In turn, the other lower level inputs need to be introduced by the user as parameters and include the following:

- The initial weight
- The target weight at the end of the program
- The length of the program, or more specifically how aggressive the user wants to be
- The Gender – Male/Female
- The Age – The physical age of the person
- The Physical Activity Factor – How active is the individual
- The Energy Intake – The amount of energy that the individual is receiving in a day

The model parameters with the units of measure and range are listed in Table 8.

The following formulas not described in Chapter IV were used in the model:

$$\text{Self} - \text{Imposed Weight Loss} = \int (\text{Target Weight} - \text{Initial Weight}) / \text{Duration} \quad (20)$$

Equation 20 defines the weight loss change based on the initial weight of the individual, goal at the end and duration. The desired rate of change is continuously compared to the actual change by the Weight Step formula explained below:

$$\text{Change in Weight} = (\text{Weight step} - \text{Expected Weight}) / \text{Delay} \quad (21)$$

Table 8 - Model Parameters

	Name	Definition	Units	Example	Range
1	<i>Initial Weight</i>	The current weight	kilograms	150 kg	50 to 300
2	<i>Target Weight</i>	The expected weight at the end of the program	kilograms	80 kg	50 to 200
3	<i>Gender</i>	Male/Female	Unitless	Male	Male/Female
4	<i>Age</i>	The physical age	years	35	20 to 90
5	<i>Physical Activity Factor (PAF)</i>	A coefficient that depends on the level of activity	Unitless	1.44	1.0 to 2.5
6	<i>Energy Intake</i>	The amount of calories or MJ that is received	MJ	14,322	4,000 to 24,000
7	<i>Duration</i>	Time to adjust to the expected weight	Days	360	1 to 720

This part of the dynamic model will account for the delay in adopting a change by the body in the future. The body transformation does not happen instantly when we deal with obesity control. For example, a certain intervention in diet at a particular point in time will create a response at a later interval. Moreover, it takes a certain amount of time for the body to stabilize and adapt to the change (the homeostasis mechanism).

The benefit in considering the delay is the ability of the model to accurately simulate smaller intervals of time. At this stage of development, however, the delay is not yet considered. As presented in more detail within Chapter V, the model simulates the weekly weight loss. In order to allow for smaller intervals of time, the delay needs to be considered. The model accurately predicts the weight change based on the given parameters from one week to another. By accounting for delays, the model will be useful on a daily basis. The benefit of being able to simulate accurately shorter intervals of time

is to have a better understanding of the cause and effect relationship. That is, due to the rather long interval of time when simulating weekly, the impact of certain events is lost due to the homeostasis effect. As an example, overeating produces a jump in weight on in a relatively short amount of time after which the body tends to move back towards the equilibrium. That might not complete the loop (go back to the same point where the individual was before overeating) unless the caloric deficit compensates for the excess. However, the absolute difference is much smaller and such difficult to associate with a certain event (e.g. overeating).

Equation 22 completes the iteration loop initiated by the user that is continuously updated with the actual weight change as follows. Although not explicitly specified by the formula retrieved directly from Vensim, the constant is “*Self Imposed Weight Loss*”.

$$\text{Expected Weight} = \int \text{Change in Weight} \quad (22)$$

The formula in Equation 23 is comparing the change in body mass due to the interventions based on the personal characteristics with the Target Weight as follows:

$$\begin{aligned} \text{Actual Weight} = \\ \text{IF THEN ELSE}((\text{Basic BM} + \text{BM CEtTissue}) - \text{Expected Weight} < \\ \text{Target Weight}, \text{Target Weight}, (\text{Basic BM} + \text{BM CEtTissue}) - \\ \text{Expected Weight}) \end{aligned} \quad (23)$$

Vensim is using a rather unusual way of defining the If/Then/Else condition. The way to read it is: “If (Basic BM + BM CEtTissue) – Expected Weight < Target Weight then use Target Weight. Otherwise use Expected Weight”. The same procedure is used in all of the If/Then/Else functions.

If the target was achieved, the model does not allow further change in weight without the user modifying the target or potentially the user gaining back a certain amount of weight beyond the target. The model remains at the Target Weight.

Equation 24 is used for checking the actual achievement of the self-imposed weight loss program as follows:

$$\text{Weight Step} = \text{IF THEN ELSE}(\text{Self Imposed Weight Loss} < \text{Actual Weight}, \text{Actual Weight}, \text{Self Imposed Weight Loss}) \quad (24)$$

If the step defined by the user is more aggressive than the actual weight loss (i.e., the target was to achieve 103 kg and the actual was 105 kg), instead of moving to the next step, the model maintains the old target until that is achieved (i.e., 103 kg). This prevents unrealistic goal setting by using a short period of time for expecting to achieve a dramatic change in weight.

Equation 25 is used for measuring the change in body mass due to the energy spent by the user in transforming the food in either fat or lean tissue, as expressed below. The initial condition is the “*Initial Weight*”.

$$\text{BM CEtTissue} = \int \text{Change in BM to Build New Tissue} \quad (25)$$

Equation 26 focuses on the Basic BM since it is commonly considered as influential to the body mass elements of: Basal Metabolic Rate, Physical Activity and Energy Intake. The initial condition is also the “*Initial Weight*”. The relationship is as follows:

$$\text{Basic BM} = \int \text{Main Change in BM} \quad (26)$$

#### 5.4. Model Operation

In order to provide a clear understanding of how the model operates, a series of simulations were performed by iterating with different parameter settings. Table 9 summarizes the five simulation scenarios explored based on the variable and constant parameters listed.

The model can be used in two ways as either reactive or preventive. In the reaction mode, the individual's goal is to lose weight, based on their current weight exceeding the amount that is desired. The second alternative (preventative) involves the use of a dynamic model to build a strategy for maintaining a desired weight.

Table 9 - Simulation Scenarios

Scenario	Parameter	Set Value	Constant or Variable?	Scenarios
1	Initial Weight	150	Constant	Maintenance Mode – Sustaining a certain weight
	Target Weight	80	Constant	
	Duration	360	Constant	
	Age	35	Constant	
	Gender	Male	Constant	
	PAF	1.44	Constant	
	Energy Intake	16.6	Constant	
2	Initial Weight	150	Constant	PAF-2&EI-8: Both, factors modified: PAF = 2 & EI = 8 MJ/day
	Target Weight	80	Constant	
	Duration	360	Constant	
	Age	35	Constant	
	Gender	Male	Constant	
	PAF	2.0	Constant	
	Energy Intake	8.0	Constant	
3	Initial Weight	150	Constant	PAF-2: Maximum PAF possible. Probably unrealistic for the majority
	Target Weight	80	Constant	
	Duration	360	Constant	
	Age	35	Constant	
	Gender	Male	Constant	
	PAF	2	Variable	
	Energy Intake	14.567	Constant	
Cont. on the next page				



Scenario	Parameter	Set Value	Constant or Variable?	Scenarios
4	Initial Weight	150	Constant	EI-8: Energy Intake 8 MJ/day from 14.567 MJ/day
	Target Weight	80	Constant	
	Duration	360	Constant	
	Age	35	Constant	
	Gender	Male	Constant	
	PAF	1.44	Constant	
	Energy Intake	8.0	Variable	
5	Initial Weight	150	Constant	Original conditions
	Target Weight	80	Constant	
	Duration	360	Constant	
	Age	35	Constant	
	Gender	Male	Constant	
	PAF	1.44	Constant	
	Energy Intake	14.567	Constant	

The results of the five different scenarios are presented in Figure 33.

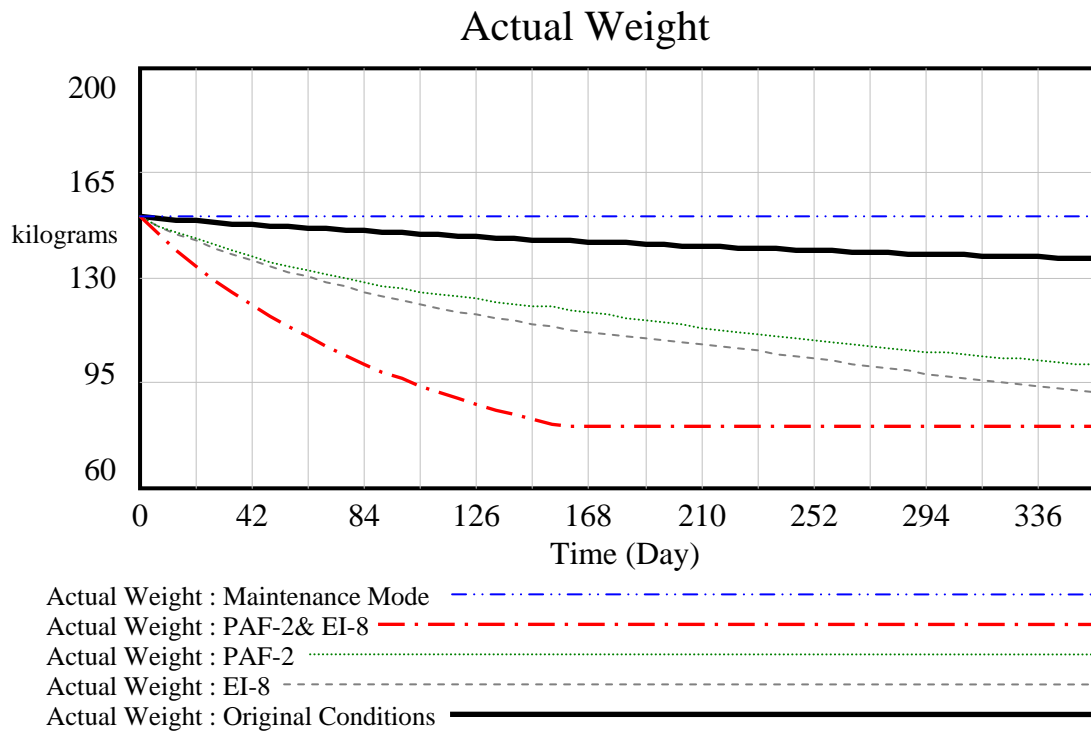


Figure 33 - Simulation Data

Observations related to the simulated scenarios presented in Figure 33 include the following:

- Even by adjusting the PAF to an extreme (e.g.,  $PAF = 2$ : Scenario 3 - high intensity of physical activity, competitive athlete), the weight loss is clearly not as aggressive compared to a significant reduction in Energy Intake (i.e., see Scenario 2 for comparison). Consequently, it can potentially be concluded that the control of what an individual eats might have more influence on a weight loss program than exercising extensively.
- When both parameters are adjusted individually towards the direction of losing weight (e.g. less calorie and more physical activity) and changed within the same timeframe (i.e., as in Scenario 4), weight loss is greater than when either one of them are adjusted separately.
- While for weight loss there is the need for more aggressive strategies, for maintaining a healthy weight, we need to find the balance between the PAF, other sources of energy expenditure, and Energy Intake. As an example, to maintain weight at the 150 kilograms level, a 35 years old male that is moderately active ( $PAF = 1.44$ ) needs to keep their EI level at 16.6 MJ/day (i.e., Scenario 5).
- When both interventions happen simultaneously (e.g., a very high activity level and a reduction in Energy Intake), the individual very quickly achieves the target weight (i.e., Scenario 4). Going beyond the fact that the rate of losing weight might not be healthy (e.g. has some side effects), the model does not exceed the target weight once it is achieved. The individual would need to

intervene and reset the goal to a lower level before the model allows more weight reductions.

Many other scenarios can be simulated. Quantitative data about the runs can also be acquired as in Table 10, where each different strategy is compared. An individual can see the progress expected after each step is performed in comparison to the other scenarios.

All other variables and constants defined in the model can be plotted so the behaviour of each one can be analysed. As an example, another variable such as *BMCEtTissue* is provided in Figure 34. The energy used to transform the food into either fat or lean tissue is relatively small in comparison to both the Basal Metabolic Rate and energy used when performing sustained physical activity.

Table 10 - Quantitative Data of Simulation Runs

"Actual Weight"	Actual Weight				
Runs:	150	150	150	150	150
Maintenance	150.06	144.17	147.28	147.16	149.50
Mode	150.11	138.89	144.92	144.65	149.15
PAF-2& EI-8	150.16	133.95	142.72	142.25	148.67
PAF-2	150.20	129.31	140.66	139.97	148.34
EI-8	150.25	124.95	138.74	137.80	147.88
Original	150.28	120.87	136.94	135.73	147.56
Conditions	150.33	117.04	135.26	133.77	147.11
	150.36	113.45	133.69	131.89	146.82
	150.40	110.08	132.22	130.11	146.38
	150.42	106.92	130.85	128.41	146.11
	150.45	103.96	129.57	126.80	145.69
	150.46	101.18	128.37	125.26	145.42
	150.50	98.57	127.26	123.80	145.02
	150.50	96.12	126.22	122.41	144.77
	150.53	93.82	125.24	121.09	144.37
	150.53	91.66	124.34	119.83	144.14
	150.56	89.63	123.49	118.63	143.76
	150.56	87.73	122.70	117.50	143.54

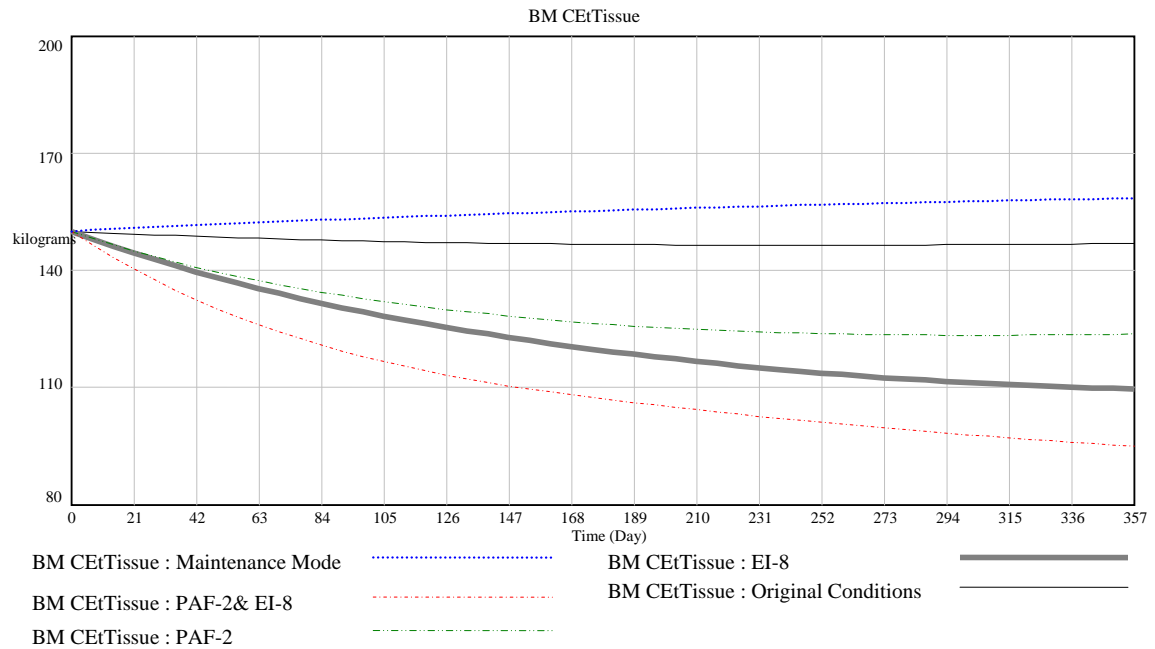


Figure 34 – BM CEtTissue

Table 11 presents the count, minimum, maximum, mean, median, standard deviation and norm of each individual scenario.

Table 11 - Model Statistics							
Variable	Count	Min	Max	Mean	Median	StDev	(Norm)
Actual Weight for Time (Day) from 0 to 357 Runs:		Maintenance Mode		PAF-2& EI-8		PAF-2	EI-8
Actual Weight	52	150	150.59	150.40	150.45	0.1624	0.0010
: PAF-2& EI-8	52	80	150	92.43	80	19.50	0.2109
: PAF-2	52	100.86	150	118.90	116.87	13.31	0.1119
: EI-8	52	91.71	150	113.76	110.59	15.77	0.1387
: Original Conditions	52	136.07	150	141.99	141.44	4.013	0.0282

The bar chart illustrated in Figure 35 is an alternative method to more clearly highlight the differences in final weight achieved through the various scenarios discussed.

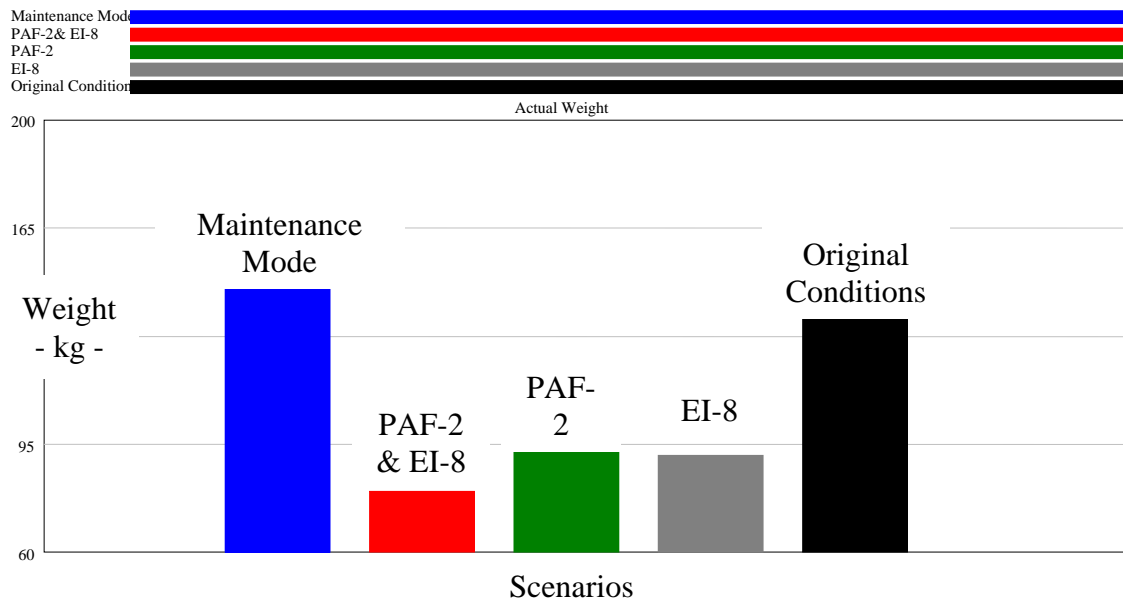


Figure 35 – Bar Chart with Weight Achieved

## CHAPTER VI

### MODEL RESULTS AND VALIDATION

#### 6.1. Comparative Analysis

In order to understand the usefulness of the model, as well as test and validate the results, a set of techniques have been used as presented in this chapter. Actual field data was provided by a clinic specializing in weight loss. The patients went through a very particular type of diet based on Human Chorionic Gonadotropin, a hormone found in the urine of pregnant women. That allows the patients not experience hunger, which in turn allows them to consume only 500 calories/day, a much lower amount than what they would normally consume. That is complemented by a particular choice of foods, administered under the supervision of the trained personnel. The patients record the calories consumed as well as what type of food/drinks are part of their daily diet. The program varies in length and the patients measure their weight weekly. There were several other input parameters required as presented in the previous chapters that were provided by the clinic. They include: *Age* (of the individual), *Gender*, *Calories* and a qualitative assessment of the *PAF*. A weekly recording of the actual *Weight* of the individual was also provided. A portion of the data structured is shown in Appendix D.

The significance of the column headers is as follows:

- EI1-M38 – energy intake of the first individual who is a 38 years old male
- W1-M38 – weight of the first individual in kilograms
- OMW1-M38 –weight predicted by the model

Similarly, the second individual is a female and the logic behind the column headers remains the same as the above (EI2-F39 stands for the energy intake of the second individual who is a 39 years old female).

The following graphs (Figures 36 to 42) present the theoretical (modeled) weight progression versus the actual data obtained from the weight loss clinic.

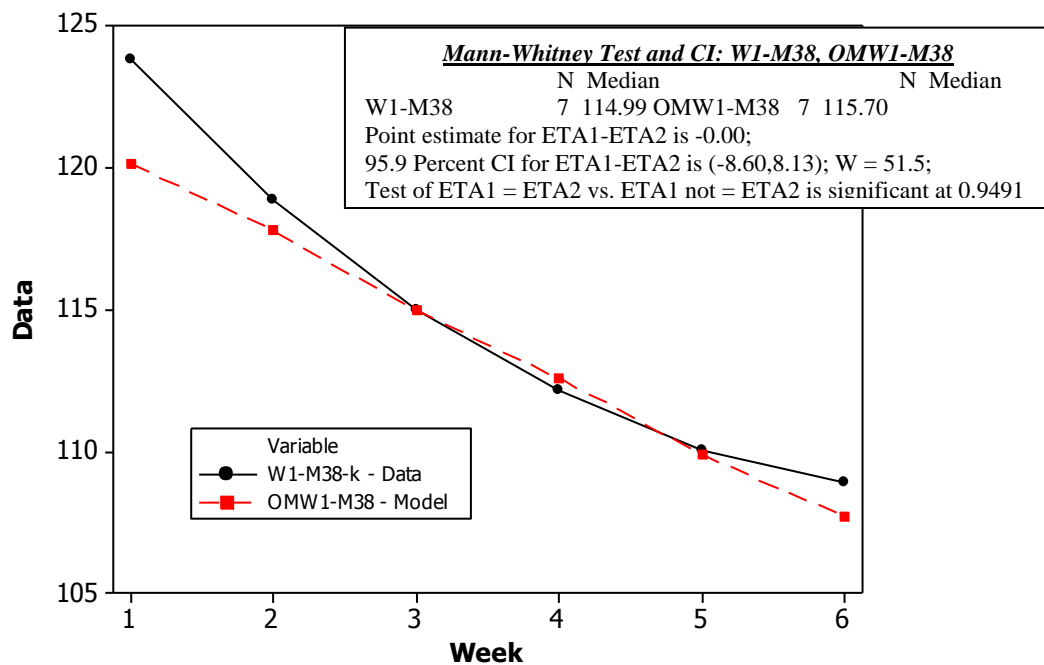


Figure 36 – Person 1 Weight Progression versus Model

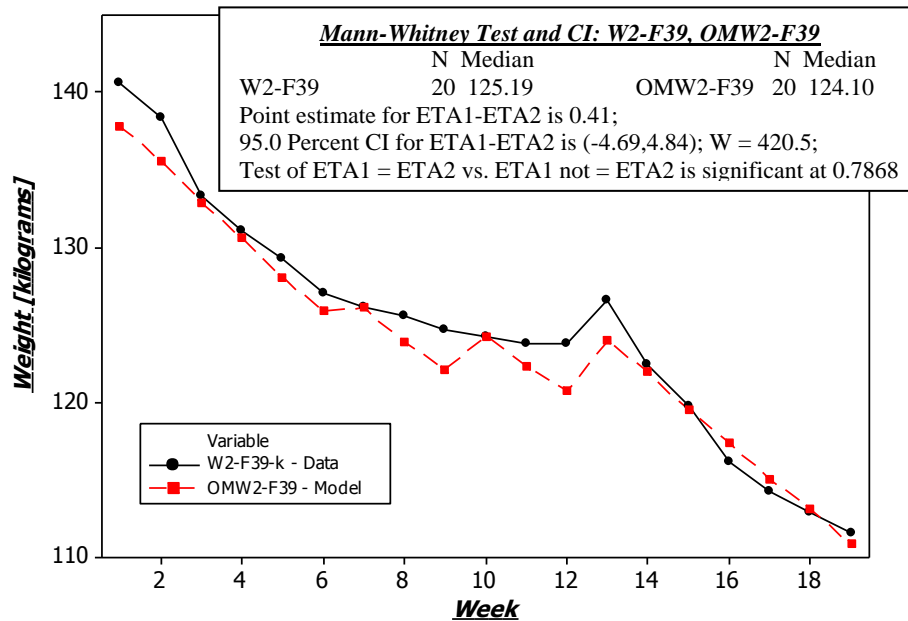


Figure 37 - Person 2 Weight Progression versus Model

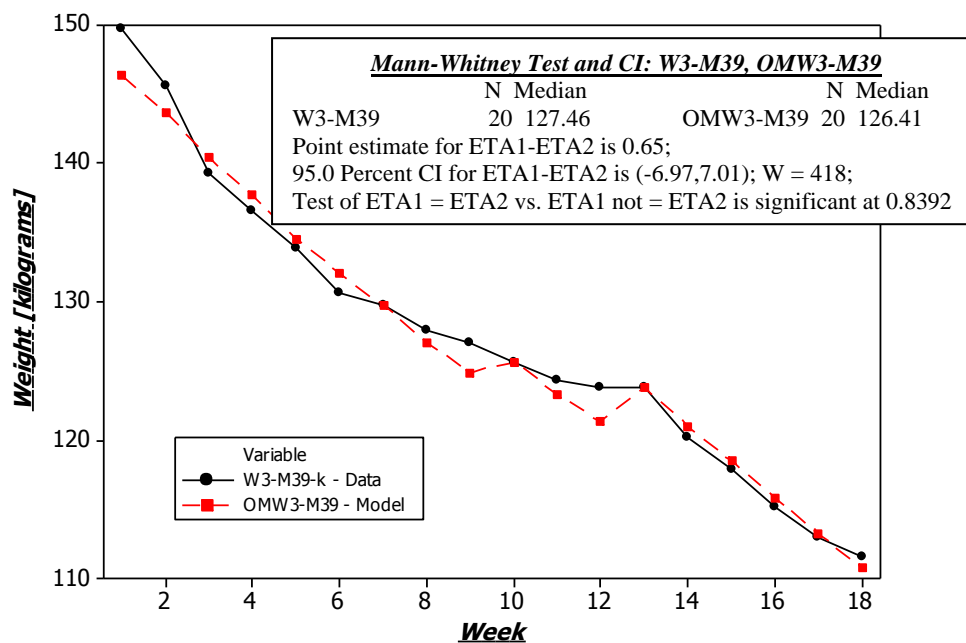


Figure 38 - Person 3 Weight Progression versus Model



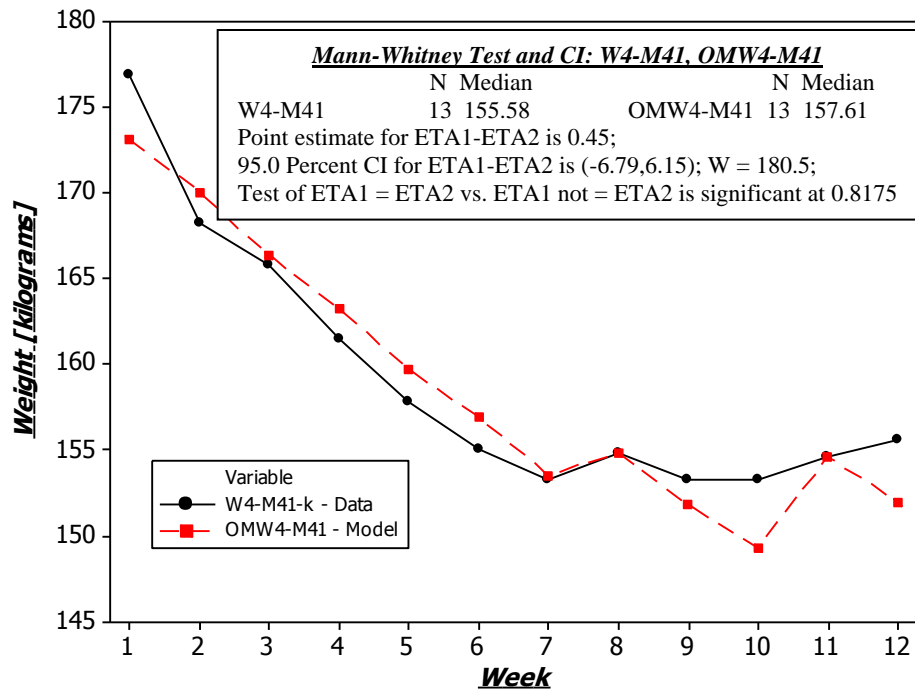


Figure 39 - Person 4 Weight Progression versus Model

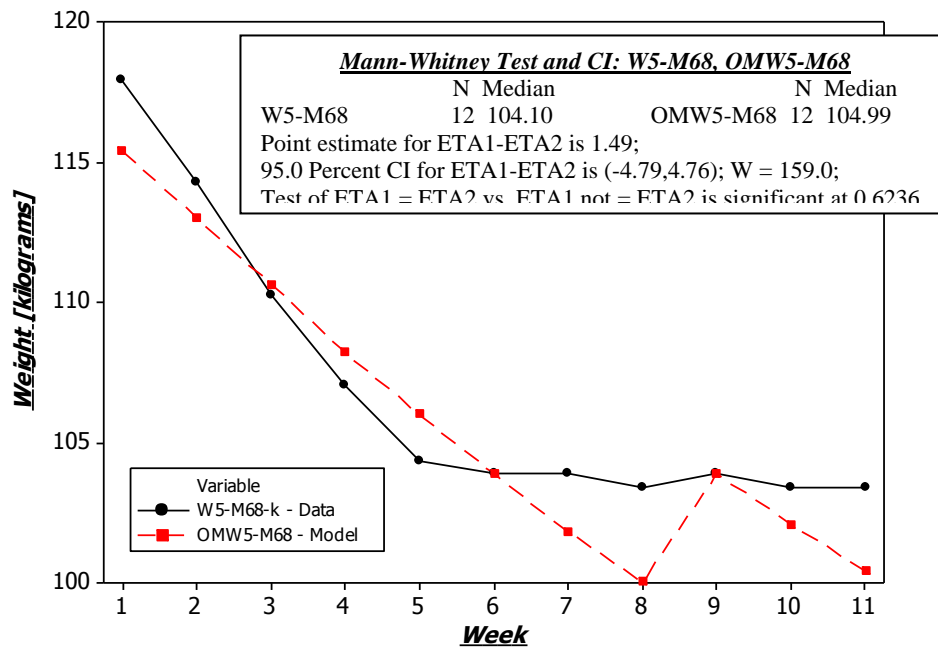


Figure 40 - Person 5 Weight Progression versus Model

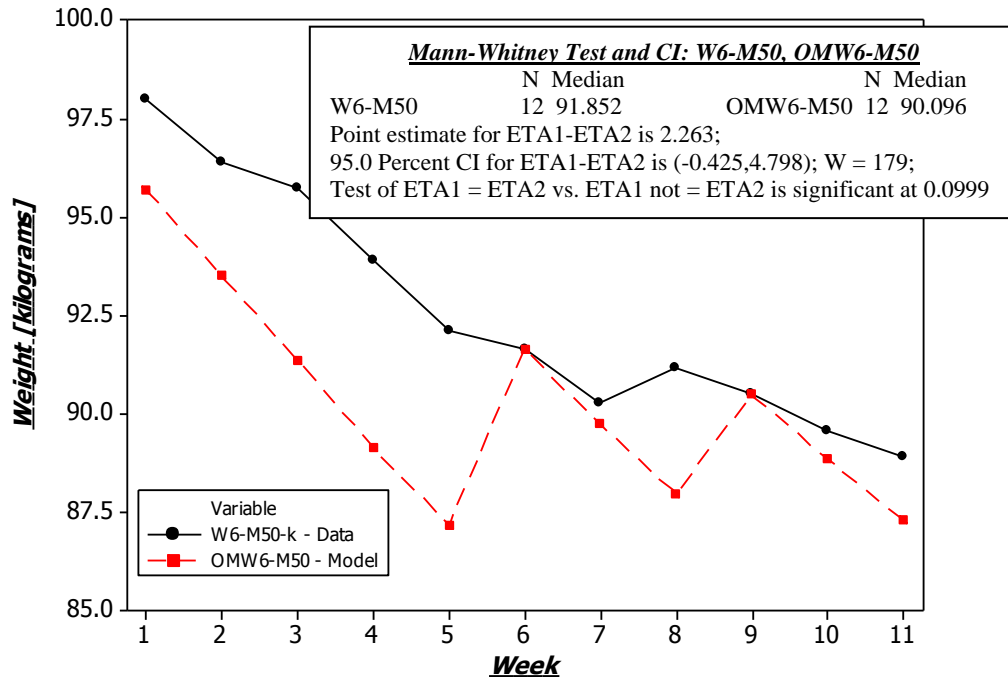


Figure 41 - Person 6 Weight Progression versus Model

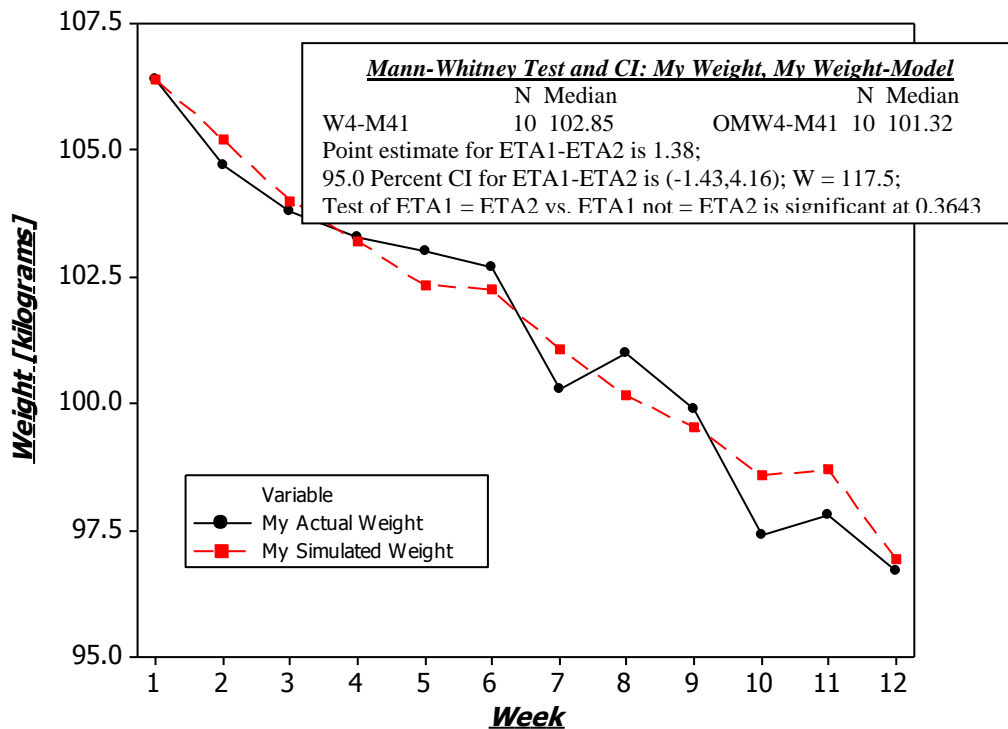


Figure 42 - My Weight Progression versus Model

The graphs presented in Figures 36 to 42 illustrate how close (not significant statistical difference and  $R^2$  around 90%) the predictive model approximates the actual field data. To reinforce the conclusions related to the accuracy of the dynamic model, non-parametric comparisons between the original data and simulated data have been performed. Particularly, the results of the Mann-Whitney non-parametric procedures are incorporated in the graphs they represent. Excepting the subject number 6 which had a p value less than 0.1 (but still over 0.05), all the other non-parametric tests have p-values well over 0.1. That shows confidence in the fact that there is no statistical difference between the model and the field data.

The decision for using non-parametric instead of parametric procedures was made based on the fact that there is naturally a lower boundary, as well as an upper boundary, in any weight loss/gain pursuit. First of all, the weight cannot be negative. Moreover, it is understood within the scientific community that there is a certain value above which the weight loss is unhealthy or even impossible without jeopardizing the overall health status.

The following graphs (43 to 49) illustrate individual correlations between the variables representing theoretical or simulated weight loss against the actual field data.

Figure 43 shows my personal experiment during a weight loss program. The simulated data follow very closely the one that I personally monitored and recorded, similarly to the one obtained from the Weight Loss clinic.

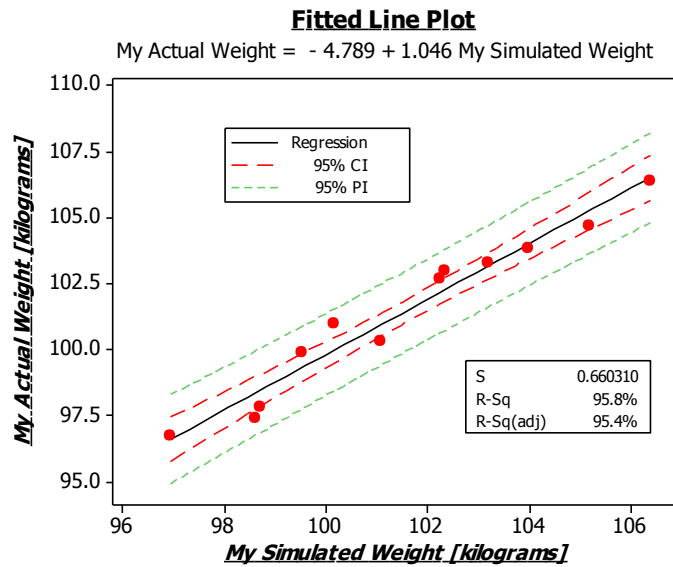


Figure 43 – My Weight Loss versus Model Prediction

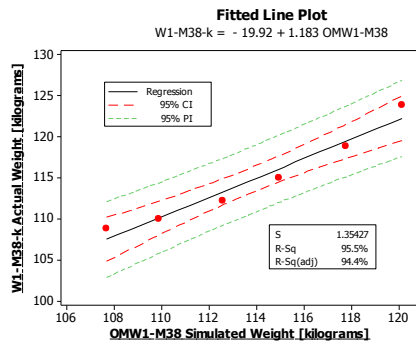


Figure 44 – Weight Data Person 1

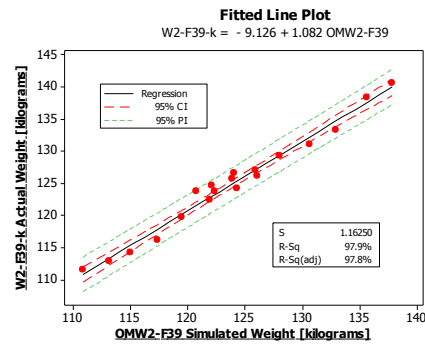


Figure 45 – Weight Data Person 2

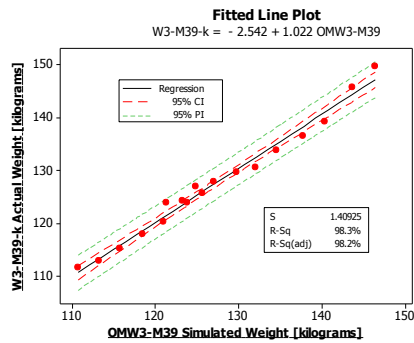


Figure 46 – Weight Data Person 3

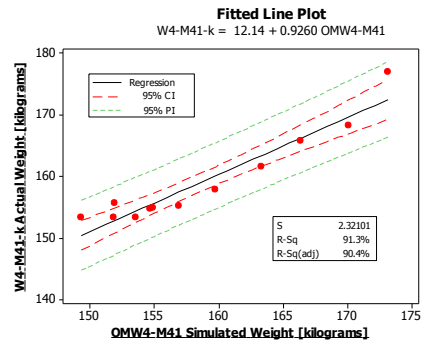


Figure 47 – Weight Data Person 4

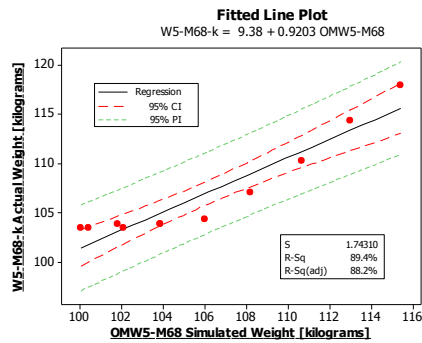


Figure 48 – Weight Data Person 5

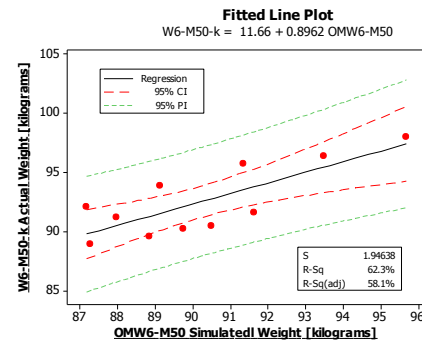


Figure 49 – Weight Data Person 6

It is noteworthy that all field data available graphically have a good fit relative to the models, where  $R^2$  is greater than 90%, with the exception of one data point: Person 6. It is assumed that the outlier data is due to one patient not accurately reporting the progress of their weight loss effort.

In order to better quantify and summarize the capability of the model to simulate a weight loss endeavour, the available data from the seven patients, including the outlier, were grouped into two sets. The first set contains all data representing the weight loss progress recorded by the obesity clinic during the real life weight loss programs and is entitled “Actual”. The second column contains all data predictions based on the model and is entitled “Simulated”. A portion of the data structure is presented in Appendix D.

Figure 50 is a graph illustrating a very strong relationship between the Actual versus Simulated data sets, with an  $R^2$  of 99.4%, and very tight confidence and prediction intervals. There is a more detailed statistical analysis included in the Appendix D.

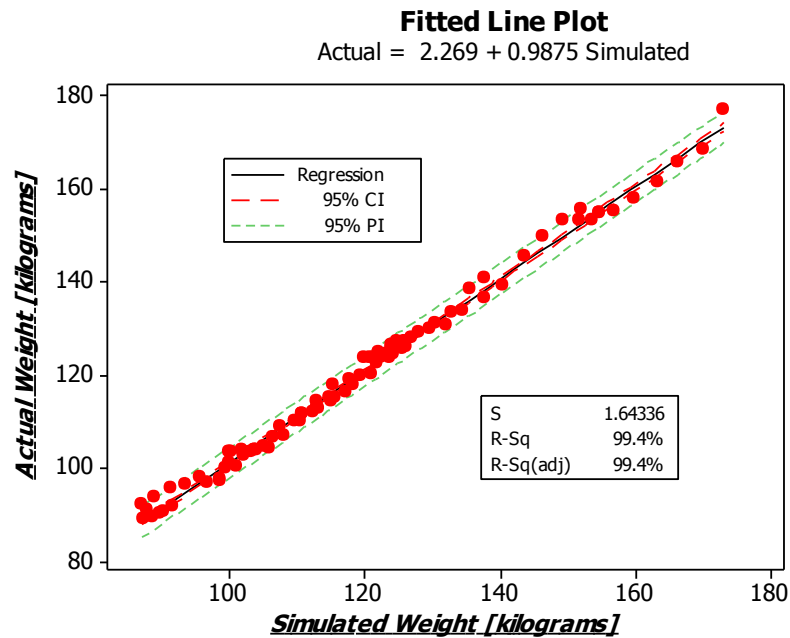


Figure 50 – Comparison of Actual vs. Simulated Weight Loss for All Data

In Appendix D, the data sets are compared for meeting the conditions of a regression analysis. As observed from the graphs and analyzed through the Kolmogorov-Smirnov normality test, both data sets (Actual and Simulated) follow normal distribution. In addition, the residuals meet the requirements for a meaningful regression analysis.

The following conclusions can be made based on data in Table 12:

- As a predictor, the Simulated data very closely predicts the Actual since the p-value is approximately zero
- The prediction equation for the merged data is:  $Actual = 2.27 + 0.988 * Simulated$

Table 12 – Statistical Analysis for Regression

Regression Analysis: Actual versus Simulated						
The regression equation is						
Actual = 2.27 + 0.988 Simulated						
Predictor	Coef	SE Coef	T	P	VIF	
Constant	2.269	1.002	2.26	0.026		
Simulated	0.987530	0.008281	119.26	0.000	1.000	
S = 1.64336 R-Sq = 99.4% R-Sq(adj) = 99.4%						
PRESS = 249.751 R-Sq(pred) = 99.35%						

- $R^2 = 99.4\%$ ; therefore, only 0.6% of the variability remains unexplained
- The Variation Inflation Factor (VIF) = 1, so there is no autocorrelation
- The regression is significant as compared to the ANOVA table, where the p-value again is approximately zero
- The residual error is relatively small when comparing the sum of squares of the regression (235 versus 38409).

## 6.2. Sensitivity Analysis

According to Vensim, sensitivity testing is the process of changing the assumptions about the value of Constants in the model and examining the resulting output. Manual sensitivity testing involves changing the value of a Constant (or several Constants at once) and simulating, followed by a series of Constant value changes and additional simulations for generating a spread of output values.

A Monte Carlo simulation, also known as multivariate sensitivity simulation (MVSS), is a method of automating this procedure. Hundreds or even thousands of

simulations can be performed, with Constants sampled over a range of values, and model outputs stored for future analyses.

The model was used for performing a sensitivity analysis on the two main inputs (PAF and EI) against the main output (Weight). The scenarios for the sensitivity analysis are listed in Table 13. An explanation of the short-form terminology used in the table includes the following:

- Fig. – Figure number
- Distr. – Distribution; what particular type of distribution was used for generating the data
- Min. – Minimum value used from the lower side of the range
- Max. – Maximum value used from the upper side of the range
- Std. Dev. – Standard Deviation of the distribution used
- Mean – Average used for generating the data
- RN – Random Normal; the distribution used in the Monte Carlo simulation
- Var. – Variation

All other parameters in the model were kept constant during the sensitivity analysis, so the effects of EI and PAF could be observed and understood.

Since a sensitivity analysis was used in an attempt to quantify the influence of each parameter on the variability of the outcome (i.e., Weight), both the set point (mean) of the Energy Intake, as well as the Physical Activity Factor were kept constant at 10 MJ/day and 1.5, respectively.



Table 13 – Sensitivity Scenarios

Fig.	Energy Intake					Physical Activity Factor				
	Distr.	Min. (MJ/ day)	Max (MJ/ day)	Std. Dev.	Mean (MJ/ day)	Distr.	Min.	Max	Std. Dev.	Mean
51	RN	4	16	4	10	Constant				
52	RN	7	13	4	10					
53	RN	4	16	2	10					
54	Constant					RN	1	2	0.2	1.5
55						RN	1.3	1.7	0.2	1.5
56						RN	1	2	0.1	1.5
57	RN	4	16	4	10	RN	1	2	0.2	1.5
58	RN	7	13	2	10	RN	1.3	1.7	0.1	1.5
59	RN	4	16	2	10	RN	1	2	0.1	1.5
60	RN	7	13	4	10	RN	1.3	1.7	0.2	1.5

The sensitivity analysis is based on a Monte Carlo simulation. The method randomly samples from a specific distribution type in order to evaluate the behaviour of the output. Particularly in the case of the model developed by this work, a random normal distribution was chosen in spite of recommendations by the software provider for a general uniform distribution. The main reason for considering a normal distribution is based on the assumption that the individual will more often than not attempt to achieve the target, once a target is set for either the daily energy intake or the average physical activity. This means that extreme values will occur less often (i.e., mean value will be closer to the target value). Alternately by using a uniform distribution, the software would draw samples from the entire range with the same frequency (i.e., extreme values would occur as often as the target values). It is the researcher's belief that once an individual is committed to a certain regimen, they will attempt to follow it.

In Figure 51, a Monte Carlo simulation results are displayed with Energy Intake at its maximum settings, as presented in Table 13. It can be noted that in spite of an average weight decrease, the overall behaviour allows for both weight gain and a potentially

unhealthy rate of weight loss. That is illustrated by the grey area on the top of the graph that exceeds the initial weight. It is also shown by the flat area at the bottom of the graph where the model does not allow for extending the target beyond the initial goal unless the user intervenes by changing the strategy.

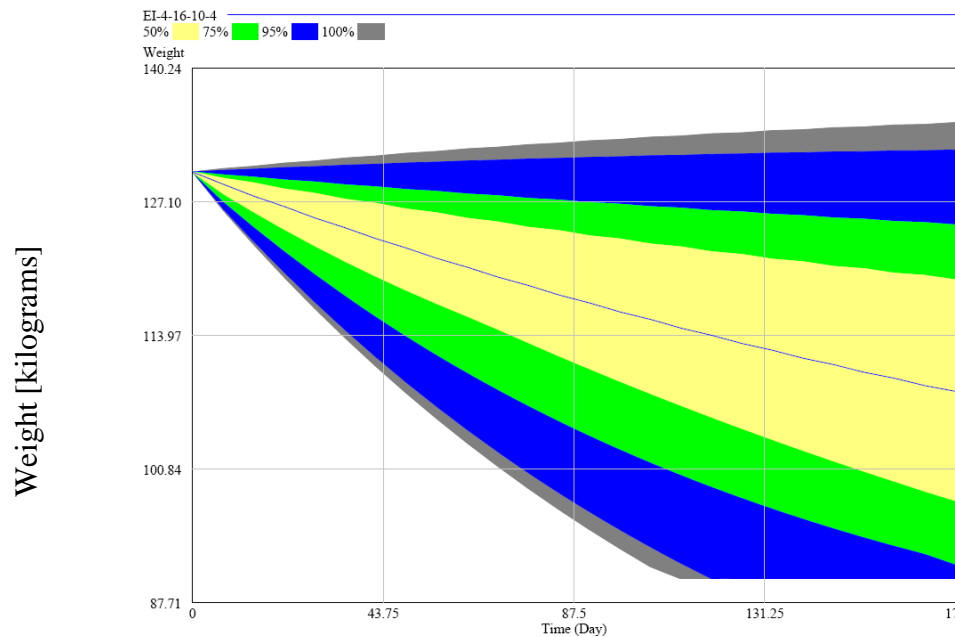


Figure 51 – Sensitivity EI with Maximum Range and Variation

For all the sensitivity analysis graphs presented in this work, for the readers with access to only a black and white version, the four ranges presented around the mean are at 50%, 75%, 90% and 100% starting from the closest to the mean and moving outwards respectively.

In Figure 52, the standard deviation and all other parameters are kept constant, with the exception of the range (i.e., minimum and maximum values) that is reduced down to 7MJ/day and 13 MJ/day, respectively. There is a notably large reduction in the variation of the results. While the average remains constant and by reducing the range, there will be no individual weight gain, though the patient might have their own unique

weight loss curve. Also related to the reduced range is the potential for eliminating unhealthy weight loss. Unhealthy weight loss in this case is defined as attempting to lose weight beyond the original target. For all graphs once the weight goal is achieved, the model does not allow for further weight loss (i.e., the non-linear behaviour remains constant at the target weight). The only way to allow additional weight loss is through patient intervention by setting a new goal.

For Figure 53, the range remains constant at the initial level, while the variation is reduced from 4 down to 2 MJ/day. This scenario allows for a combination of effects, similarly observed in the previous scenarios where fewer people gain weight overall (i.e., fewer individuals exceeding their initial weight after the study began). This fact is illustrated by any data points above a line parallel to the x-axis and starting from the initial weight. This also is an indicator for a lower potential of unhealthy weight loss.

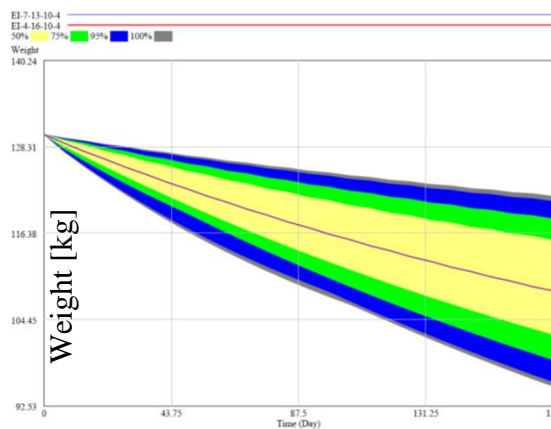


Figure 52 – EI Small Range/Maximum Variation

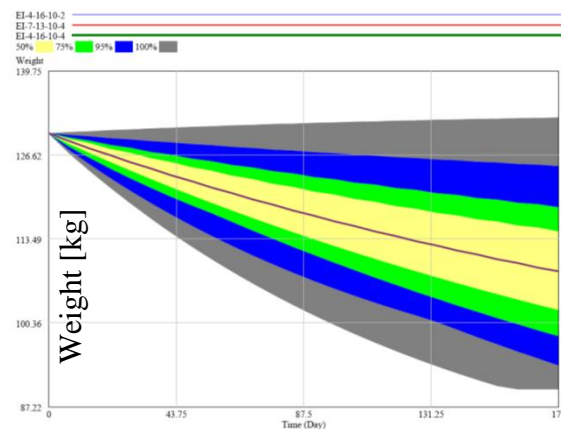


Figure 53 – EI Maximum Range/Small Variation

Figure 54 provides a similar analysis using the Physical Activity Factor. All other parameters including EI are maintained as constants so that the influence of PAF alone can be easily identified.

One aspect to consider is that, while arguably the two limits (lower and upper) used for the EI sensitivity analysis are somewhat achievable and probably sustainable for even a limited amount of time, this is anticipated not to be the case with the PAF limits. It is reasonable to believe that a person can consume energy of 16 MJ/day. In addition, they can even survive on 4 MJ/day. And while there are individuals who can sustain an activity level of 2 (close to the PAF upper limit), the vast majority of the population cannot, especially severely obese individuals. Such a level can be considered as unhealthy and potentially physically impossible to achieve and/or maintain. The lower side of the range can be classified as a sedentary type of individual and does not require additional comments since it is a common state.

Based on Figure 54, it can be concluded that all individuals are losing weight, with some at a rate faster than others.

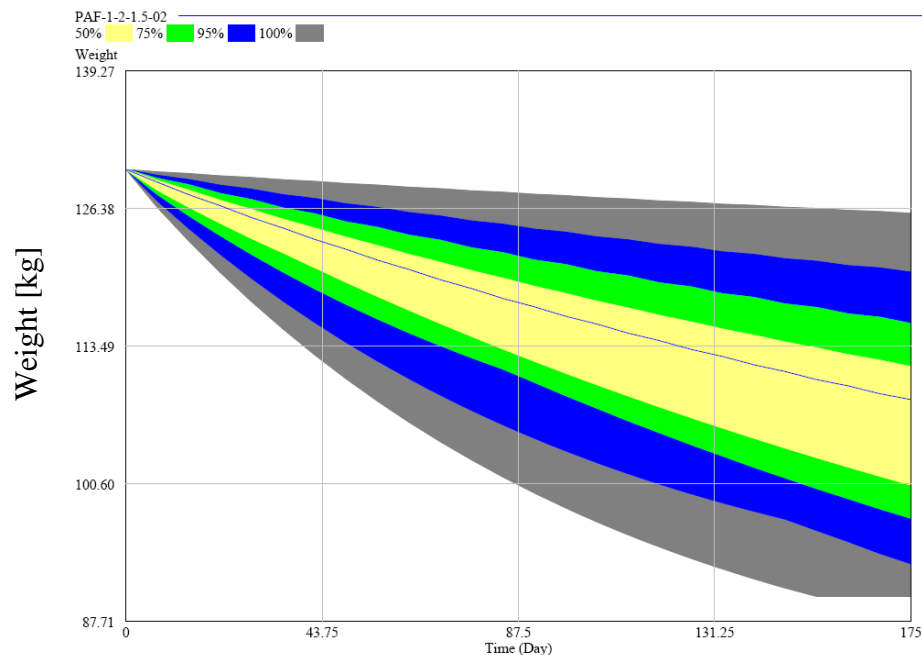


Figure 54 – PAF with Maximum Range and Variation

A smaller range of PAF (1.3 to 1.7) was used in Figure 55, while keeping the variation the same. Alternately, a smaller variation of PAF from 0.1 versus 0.2 was used in the simulation presented in Figure 56.

The behaviour of the body data provides similar trends as the EI analysis, though there is a significantly larger impact of the range consistency when comparing it to a scenario having a large range, even if the variation is smaller.

Based on these scenarios, it may be concluded that it is better to sustain a balanced program without large extremes while concentrating on program consistency. This means that maintaining a stabilized average is the preferred policy while sustaining a smaller range.

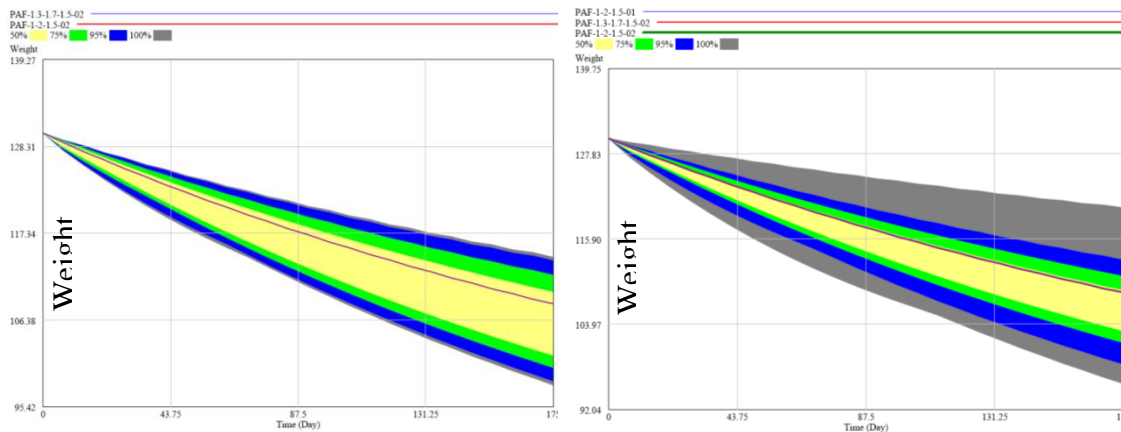


Figure 55 – PAF Small Range/High Variation

Figure 56 – PAF Large Range/Small Variation

The last four figures (57 to 60) presented under the sensitivity analysis allow for a multivariate analysis, where the two main factors of interest (EI & PAF) are simulated at the same time so that their combined affect can be observed. The sensitivity analysis can be performed with different setting. As for example, the two main factors, EI & PAF, can be set in such a way that they cancel each other on an average and analyze the impact of

different setting from the perspective of the range, variation and even the mean. More specific, from a state of equilibrium, if an individual suddenly eats and drinks more, there is a counterbalancing value of the PAF that would cancel out the impact of the additional calories (e.g. by exercising more).

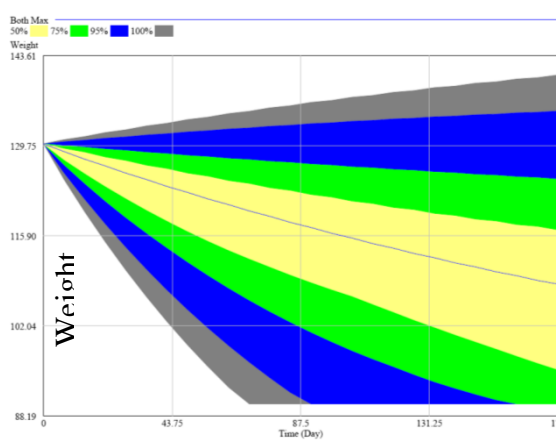


Figure 57 – EI&PAF Both Maximum

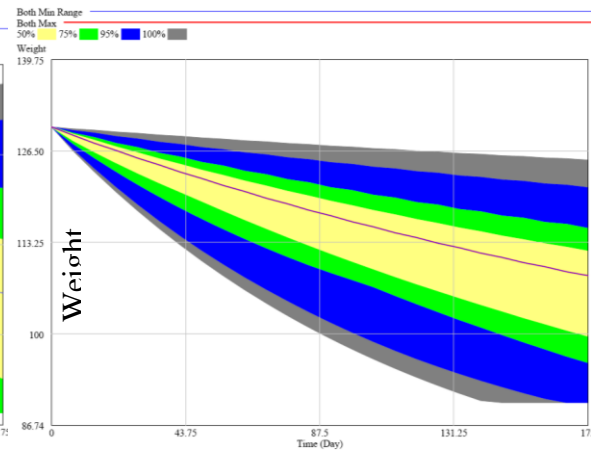


Figure 58 – EI&PAF Both Minimum

In Figure 57, both factors are simulated between the largest range and variation, while maintaining a constant mean. Thus, it can be observed that the effect noted in the univariate analysis when the two factors were individually simulated is now amplified. This means that when additional variation is induced, it leads to more extreme values of weight gain and more weight loss by patients in a more accelerated manner. The safety implications of these policies will not be discussed here.

The last three figures (Figure 58, 59 and 60) have been generated by simultaneously modeling both the EI and PAF, by holding them in between different ranges or variation levels. There are similar noteworthy trends as compared to the univariate analysis.

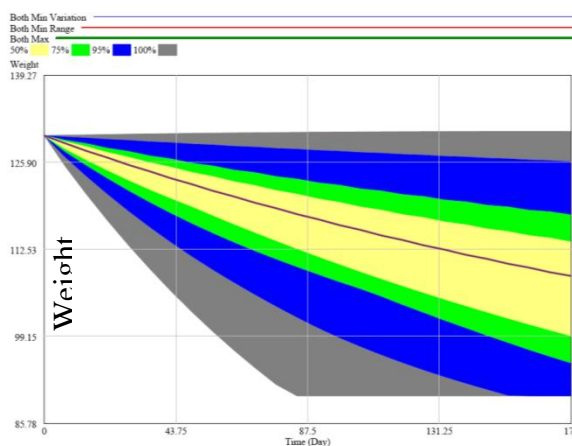


Figure 59 – EI&PAF Minimum Variation

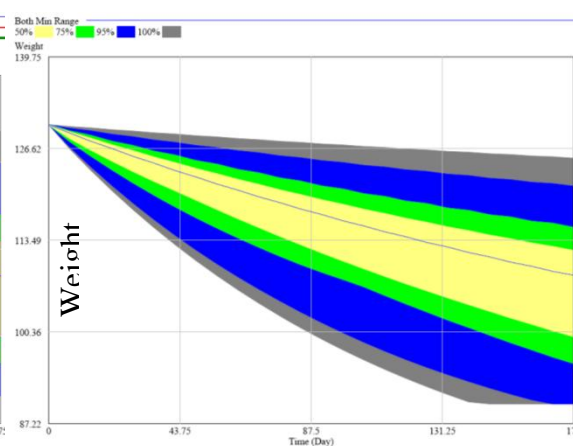


Figure 60 – EI&PAF Minimum Range

### 6.3. “What If” Analysis

There is an endless potential for simulating various “What If” scenarios by using the Obesity Model (OM). While the two most commonly understood factors (EI and PAF) have been discussed extensively in the previous two chapters, the “What If” analysis will focus on several scenarios related to other factors in the model (e.g., Age, Gender, etc.). The “What If” scenarios summary is presented in Table 14.

Table 14 – “What If” Scenarios Summary Table

	Sample1	Sample2	Sample3	Sample4	Sample5	Sample6
<b>Gender</b>	Male	Male	Male	Female	Female	Female
<b>Age (years)</b>	20	40	70	20	40	70
<b>Initial Weight (kg)</b>	130	130	130	130	130	130
<b>Target Weight (kg)</b>	90	90	90	90	90	90
<b>Length (days)</b>	180	180	180	180	180	180
<b>PAF (unitless)</b>	1.44	1.44	1.44	1.44	1.44	1.44
<b>EI (MJ/day)</b>	10	10	10	10	10	10

The weight loss progression of three male individuals is presented in Figure 61. They all had an initial weight of 130 kilograms and target weight of 90 kilograms to be achieved in 180 days, while all other parameters remained constant except for Age that varied from 20, 40 and 70 years old, respectively.

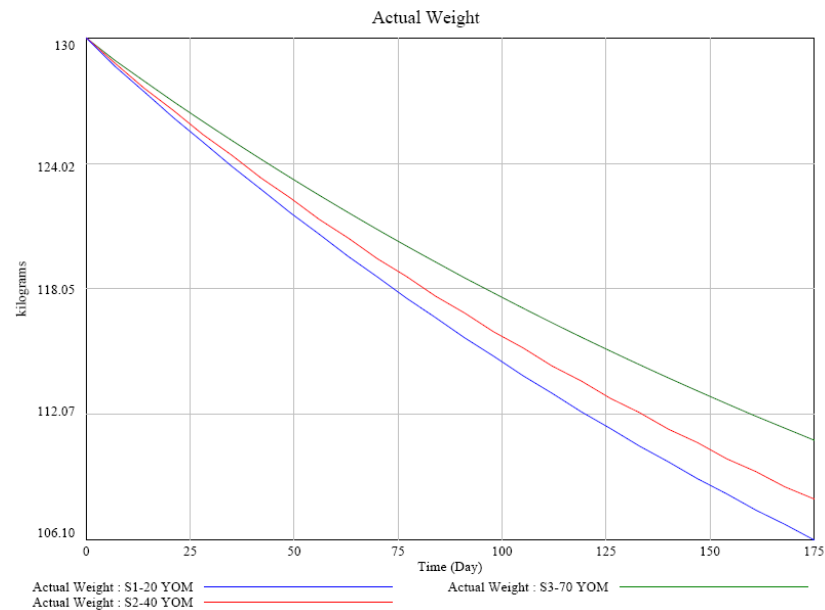


Figure 61 – Weight Loss Difference Due to Age

As illustrated in Figure 61, the weight loss rate varies over time based on Age, even if everything else remains the same. A younger individual will lose weight slightly faster than an older subject. There is a similar relationship in Figure 62 for female subject weight loss curves, where younger females will lose weight faster than older individuals, when all other parameters remain the same. It is also interesting to note that the 20 year old female is losing weight at a slower rate than the 70 year old male. To present this relationship more clearly, the weight loss for a 20 year old male is compared to a 70 year old female in Figure 63. It can be observed that after 175 days, the difference between the



two individuals is approximately 12 kilograms. The difference is due to the difference in age and gender.

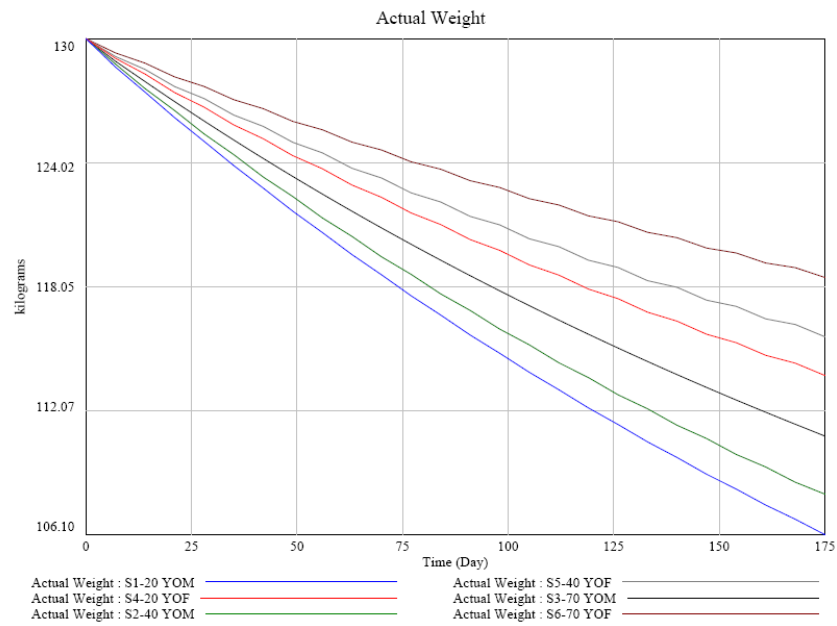


Figure 62 – Both Genders Weight Loss as a Function of Age

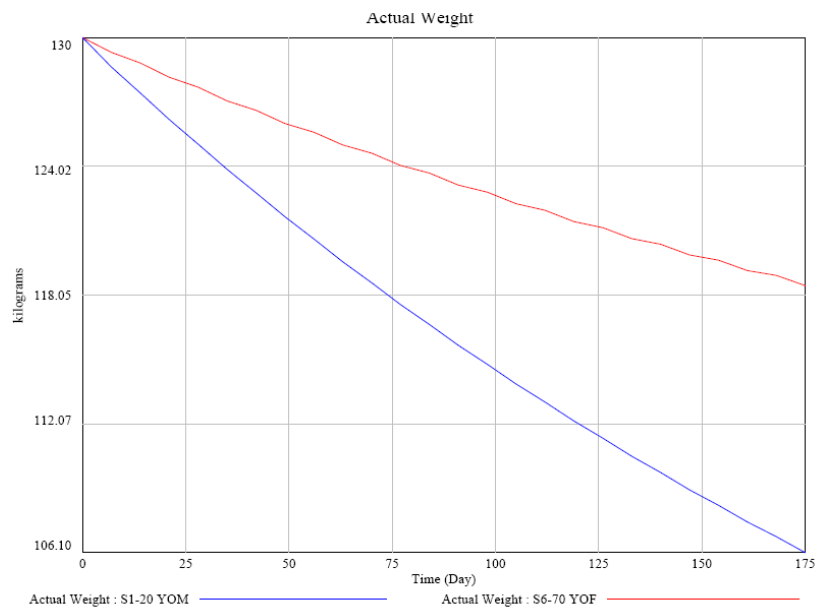


Figure 63 – Weight Loss of 20 Year Old Male vs. 70 Year Old Female

In an attempt to more deeply analyze the causes of this age related difference, the OM can be used to simulate the Basal Metabolic Rate (BMR) based on considering the same individual characteristics. In Figure 64, the different BMRs are simulated under the same conditions as above. As a general observation for all three males of different ages, the BMR is becoming lower based on the weight loss. In other words, a lighter individual requires less energy for sustaining their metabolism.

It is assumed that a 20 year old individual has higher metabolic needs for the same weight compared to someone who is either 40 or 70 years old. Consequently, it may be concluded that in order to lose weight at the same rate, older individuals need less energy to sustain their body functions. Therefore, the EI value should be adjusted, accordingly.

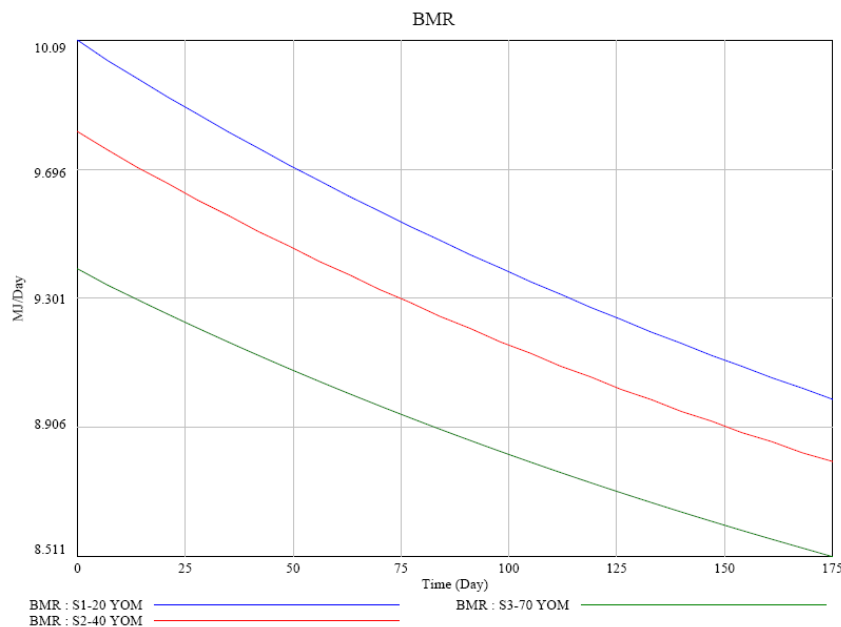


Figure 64 – BMR Change for Males Only

In Figure 65, the female and male BMR change curves are plotted together.

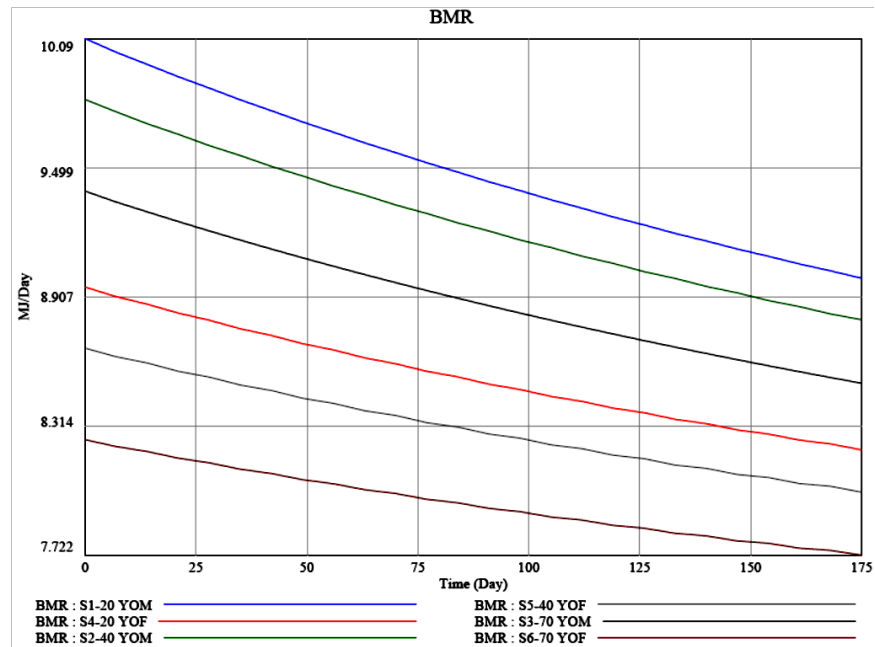


Figure 65 – BMR Change for Both Genders

The trend difference in BMR between males and females is very similar to what was previously identified for weight loss. This might suggest that the BMR change is one factor responsible for this particular behaviour. When reassessing the weight loss comparison for gender in Figure 65, the older male has a BMR higher than the youngest female. In addition, the female trend is similar to the male from the perspective that a younger individual will use more energy to sustain their body functions. In order to better understand the considerable difference generated by this parameter at a higher level, the BMR values for the 70 year old female and 20 year old male are plotted in Figure 66.

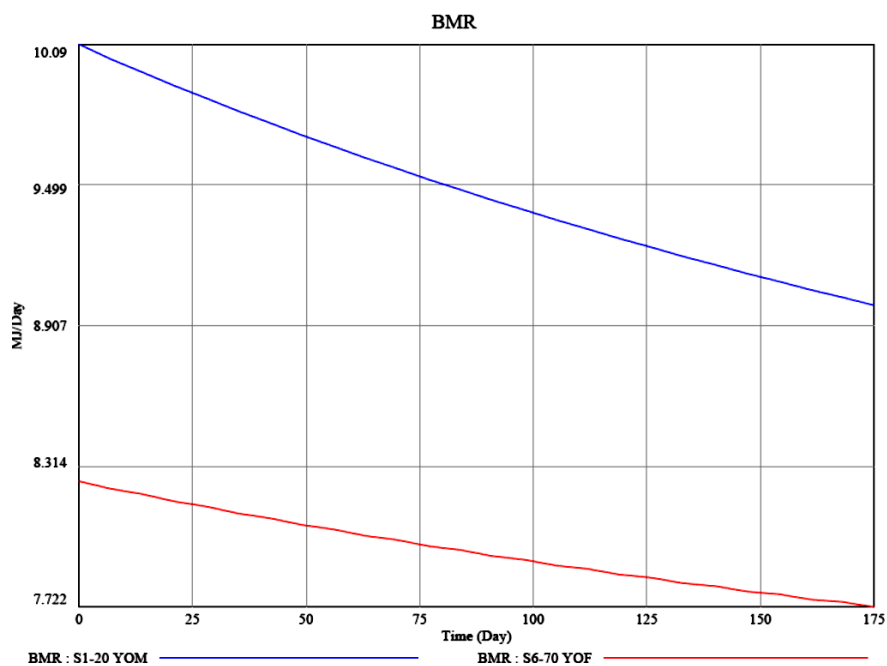


Figure 66 – BMR of 70 Year Old Female vs. 20 year Old Male

In Table 15, a side by side comparison of the weekly change in BMR is presented.

Table 15 – “What If” – Comparative Analysis of BMR for Age and Gender”

	S1-20 YOM	S4-20 YOF	S2-40 YOM	S5-40 YOF	S3-70 YOM	S6-70YOF
Time (Day)	"BMR" Runs: BMR					
0	S1-20 YOM 10.09	8.951	9.812	8.672	9.392	8.251
7	S4-20 YOF 10.02	8.908	9.755	8.632	9.341	8.220
14	S2-40 YOM 9.973	8.873	9.701	8.603	9.296	8.197
21	S5-40 YOF 9.916	8.832	9.652	8.565	9.252	8.167
28	S3-70 YOM 9.864	8.8	9.600	8.539	9.209	8.146
35	S6-70 YOF 9.810	8.760	9.554	8.502	9.167	8.116
42	9.760	8.730	9.505	8.477	9.126	8.096
49	9.709	8.692	9.461	8.442	9.086	8.068
56	9.662	8.663	9.414	8.418	9.047	8.049
63	9.613	8.627	9.373	8.384	9.009	8.022
70	9.568	8.600	9.328	8.363	8.972	8.005
77	9.522	8.565	9.289	8.330	8.936	7.978
84	9.479	8.540	9.246	8.309	8.901	7.962
91	9.435	8.506	9.209	8.278	8.866	7.937
98	9.394	8.482	9.168	8.259	8.833	7.922
105	9.352	8.450	9.133	8.228	8.800	7.897
112	9.313	8.427	9.093	8.210	8.768	7.883
119	9.273	8.396	9.060	8.180	8.736	7.859
126	9.236	8.375	9.022	8.164	8.706	7.846
133	9.198	8.345	8.991	8.135	8.676	7.822
140	9.163	8.325	8.955	8.120	8.647	7.810

The weekly data presented in Table 15 is a comparative analysis of BMR for difference age groups and gender. As a conclusion from the data, males use more energy for sustaining their body functions than females, consistently across all ages.

For adults, similar trends of the relationship between Age and BMR are presented in (Lazzer, et al., 2009). As a side note, it is interesting to see that, for children and adolescents the trend is reversed (older the child/adolescent, higher is the BMR).

Additional “What If” analyses can be performed for the parameters presented in Table 14 or for any other parameter in the OM. This is based on the interests of the individual, whether they are a researcher in the obesity field, medical doctor, patient or anyone else for that matter.

## CHAPTER VII

### RESEARCH CONTRIBUTIONS AND RECOMMENDATIONS

#### 7.1. Research Outcome

This work brings an engineering perspective to healthcare which is typically considered a non-engineering field. The key intended outcomes of the presented research are as follows:

- A conceptual system framework that advances to a methodology, leading to the development of a Predictive Analytical Model for Health Self-Care, particularly in obesity prevention.
- Integration of three different fields of knowledge that include engineering, healthcare and evidence based theories, for a seamless flow from the initial design of the system to model/simulation development and implementation.
- A method for integrating the system and subsystem designs by using a single Quality Function Deployment system.
- An engineering model based on system dynamics that can support individuals in two different ways:
  - In a clinical setting to help for the development of personalized strategies for weight loss
  - In a personal setting for helping individuals with the maintenance of their desired weight while preventing obesity.

While AMHSC will fundamentally be in support of the overall prevention system by addressing certain elements (e.g., the obesity subsystem), it is the opinion of the researcher that there is a fundamental difference that will deeply change the way personal healthcare management in particular, and healthcare in general will evolve for the future. The current systems led by facility care put the decision power in the hands of the healthcare professionals. While the risk is falsely perceived to be transferred together with the responsibility, in reality it always remains with the patients. The systems currently in place support the “risk paradigm”. However, the AMHSC promotes a true partnership approach to healthcare, where the patient becomes a partner rather than passing consumer of professional medical expertise.

Unlike any other system currently operational in healthcare, AMHSC attempts to design an element of the system that it will be in support of the current preoccupation of Canadians to improve the existing national healthcare delivery. AMHSC represents truly a patient-centered approach, as it puts the power completely in the hands of the beneficiary for managing their health, especially obesity prevention. AMHSC promotes a decision making support system based on inputs received from all individuals in their attempt to design and manage their own health and wellbeing while focusing on prevention.

This dissertation argues that in combining an engineering system design, robust decision making process and elements of system dynamics theories, the AMHSC can become a key solution in freeing up resources, and consequently reducing the cost of healthcare in North America. The proposed system attempts to build a different focus than what traditionally is recognized as healthcare, by concentrating on the patients and

their needs. AMHSC is a cornerstone of a true patient-centered system of the future, based on the individual taking ownership of their health and wellbeing. Considering that the proposed methodology may be replicated for more preventable diseases, the elimination of a wide range of conditions will lead in time to the following:

- A wide access to medical resources by the population when it is really needed, leading to an overall cost reduction for healthcare by minimizing the number of visits to the doctor. This is a natural consequence of the fact that fewer people will need medical care for what are otherwise considered preventable diseases.
- At the individual level, the system enables people to:
  - Personally manage their own disease prevention plan by using a flexible yet reliable system similar to AMHSC
  - Maintain good health in the absence of any significant chronic or acute condition
  - Manage certain preventable medical conditions from occurring
- At the national level, the overall healthcare system will benefit by improving:
  - Life expectancy
  - Quality of life
  - Population health in general without an increase in cost

## 7.2. Research Contribution

There are several aspects of this research that are either completely new to the industry or an innovative alternative approach to the traditional knowledge.



### 7.2.1. Integrated concept – Engineering, Healthcare, EBD

Figure 67 is a high-level representation of the integrated concept that directly links three different fields of knowledge for proposing a solution to the system problem.

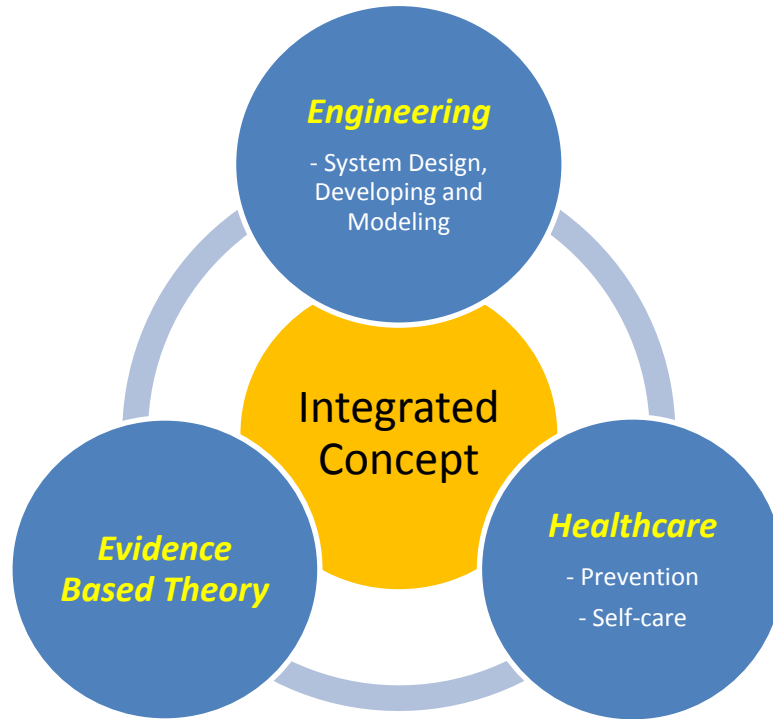


Figure 67 – The Integrated Concept

While each of these three individual fields has its own research focus, it is not common for researchers to integrate two or three fields in order to solve problems within any of the other fields. Traditionally, it is more common to utilize Evidence Based Theory (EBT) in combination with any of the other fields (e.g., engineering solutions based on data, doctors and other healthcare personnel relying on the latest research when making the most appropriate decisions, or managers retrieving quantitative data in order to suggest the best solutions). In addition, there is a new trend for engineering professionals to interact more directly with healthcare practitioners when designing equipment or hospitals, and even when improving internal processes including the

continual interest for adopting sound business concepts in healthcare to overcome the current shortage of resources.

This research builds a bridge across all three fields in an attempt to create a methodology that can be applied when developing systems for any preventable condition. While there are obvious challenges when employing all three of these major fields, it is the researcher's opinion that finding ways to look at the problems in a systemic way, and proceeding with multi-disciplinary research that uses advanced concepts from each, will be the key for identifying solutions to complex problems in the future. A more detailed representation of the methodology proposed is displayed in Figure 68.

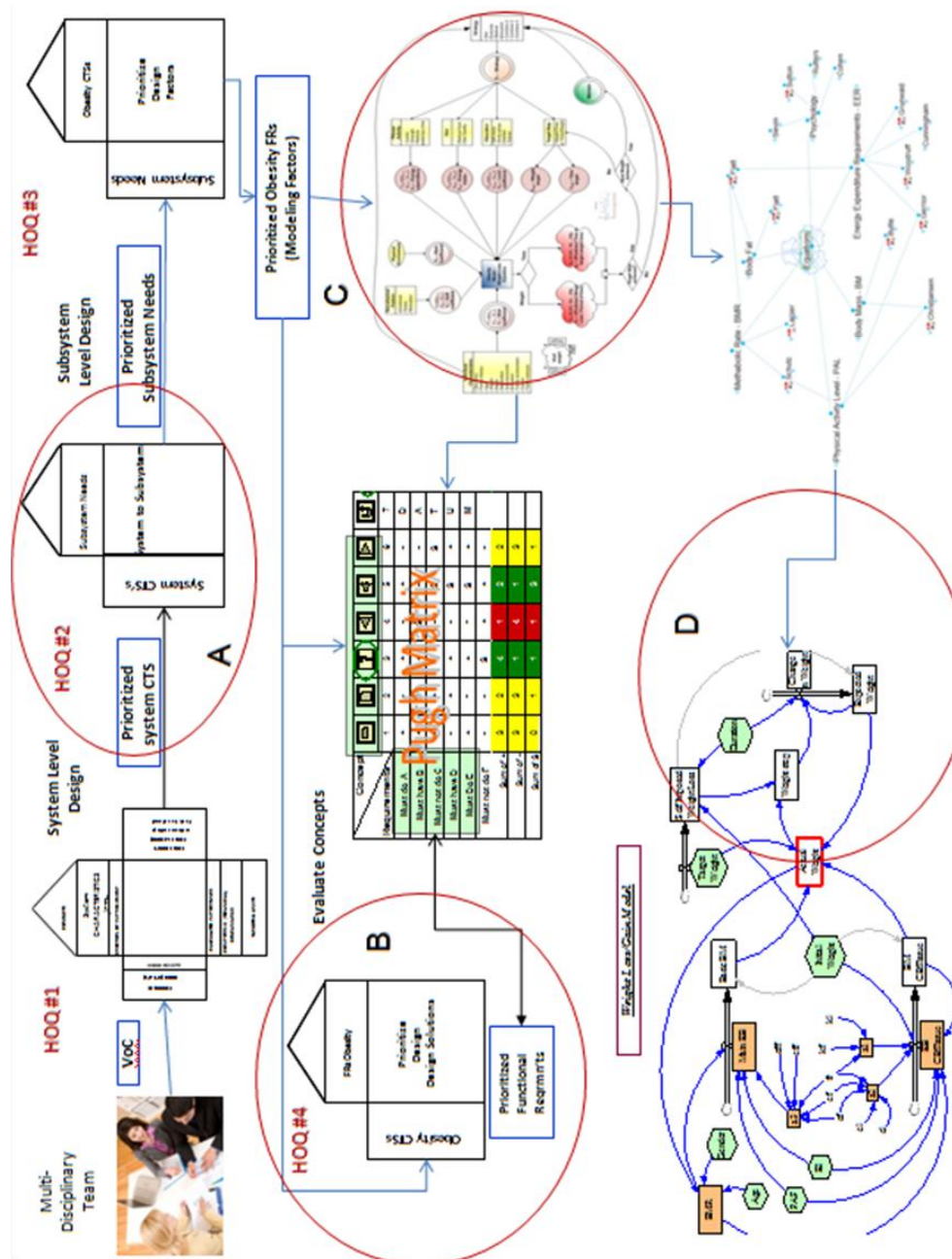


Figure 68 – AMHSC Methodology

A simplified block diagram of Figure 68 is presented in Figure 69.

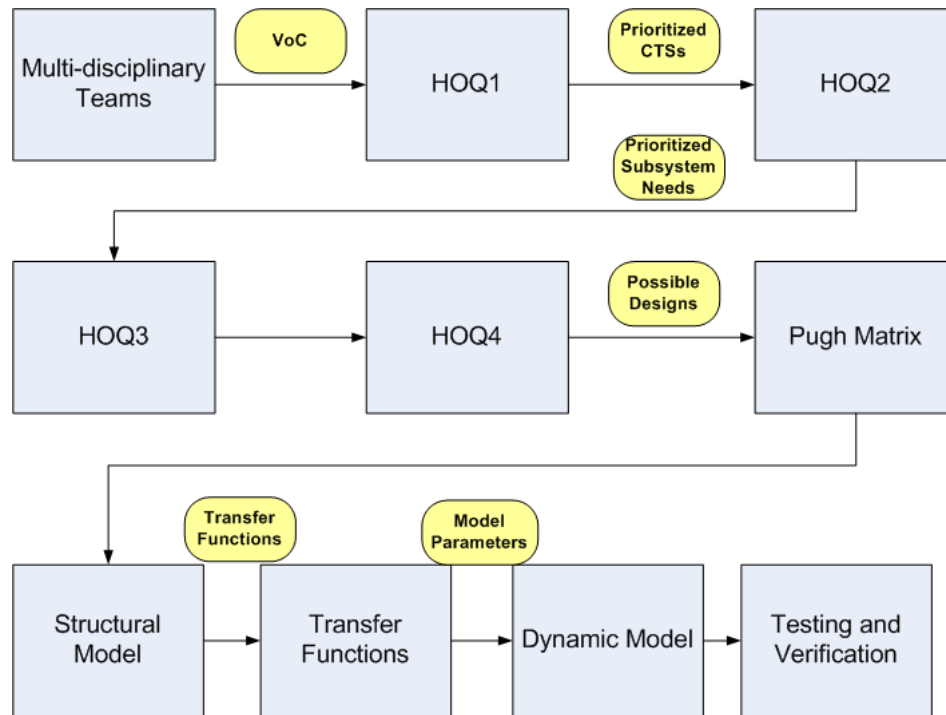


Figure 69 – Simplified Block Diagram of the Methodology

### 7.2.2. Use of QFD for direct transition system to subsystem level

Based on the practices proposed by (Akao, 1990), quality has become a leading function for new product development over the past 20 years. Quality becomes an integral part for the deployment of technology, reliability, and cost. In many of the published cases, the use of QFD has reduced the number of problems in half that were previously encountered during the initial stages of product development. Also according to (Akao, 1990), it has reduced development time between 30 to 50%, while also helping to ensure user satisfaction and increased sales.

Initially, the QFD concept was mostly used for product development. Over the past decade, there has been a trend for use of QFD in process development. The present research is introducing this concept to a different level by using it not only in system development, but also in a field that is very different from engineering.

The present innovation involves the employment of QFD to transition from the system (i.e., prevention) to one of its subsystems (i.e., obesity). This is illustrated as the circle labelled A in Figure 66. This creates opportunities for using the methodology in a wide array of subsystems development without the need of building a new QFD. Accordingly, the transition from the system to its subsystems is direct and obvious rather than done through extrapolation. The customer's voice heard at the system level is reflected at each of its components. This creates a strong link, both horizontally and vertically.

Figure 70 presents the traditional use of the QFD built for each product, process or system in development. Based on this approach, there should be two different entities separately developed that include the prevention control system and obesity system model.

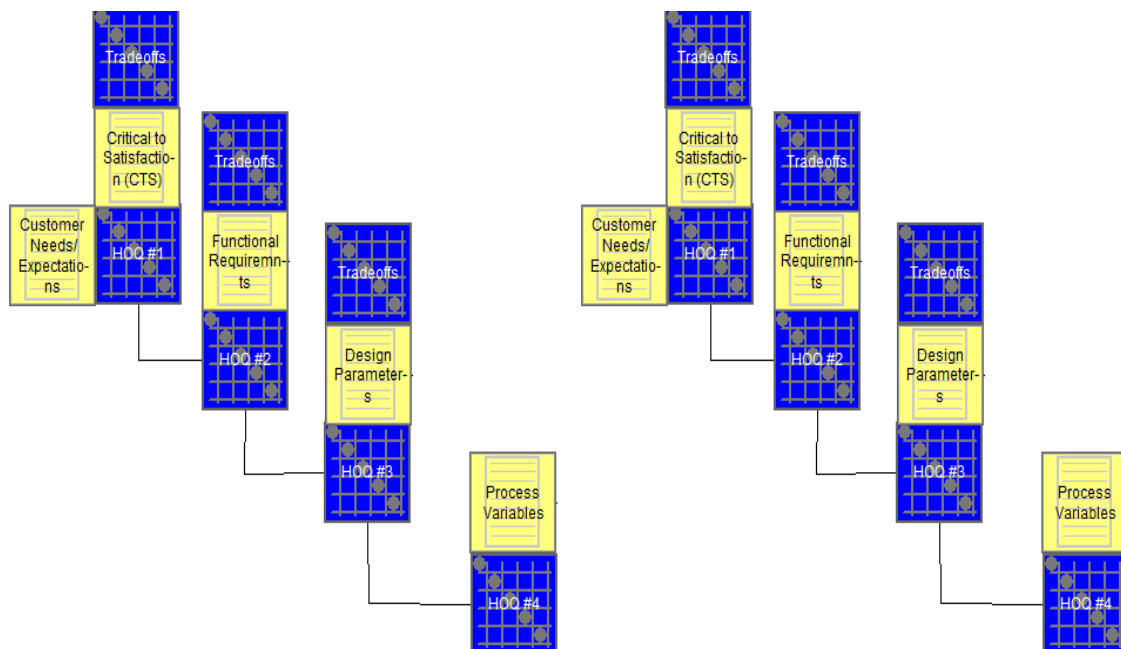


Figure 70 - Traditional QFD Approach

However, this approach has a number of shortcomings, for example:

- It is a legacy system inherited from the product QFD, thus the links to the macro-system, as well as lower level systems are not explicitly shown.
- To develop multiple products from the same family, the methodology is repeated. Unfortunately, valuable information already captured during the development of a similar product is then lost.
- If there are multiple products or parts being assembled in a final product (i.e., a higher level system), the final integration that needs to take place is neither evident nor a straightforward process.
- Even if the products or “subsystems” meet and exceed the customer requirements in their own cluster, they may not properly function once they are integrated in the final product or “system”. This means that the dynamics of an integrated system do not usually follow the dynamics of the individually developed subsystems.

Figure 71 presents how the QFD was used in this research for system and subsystem development. Some observations include the following:

- The use of QFD in the system development rather than only product or process provides opportunities at the system level that is far more complex than either product or process in general. Without the use of a structured method, it might be difficult to design or redesign a sustainable system that meets the VoC.
- There is one QFD used for both the system and its subsystems development, which provides the following:
  - Consistency in the thinking process

- A direct link and correlation between the system and its subsystems
- Arguably, the biggest advantage of all is the potential of having a unique VoC that drives the development of the subsystem towards the optimization of the whole system rather than a local, subsystem improvement

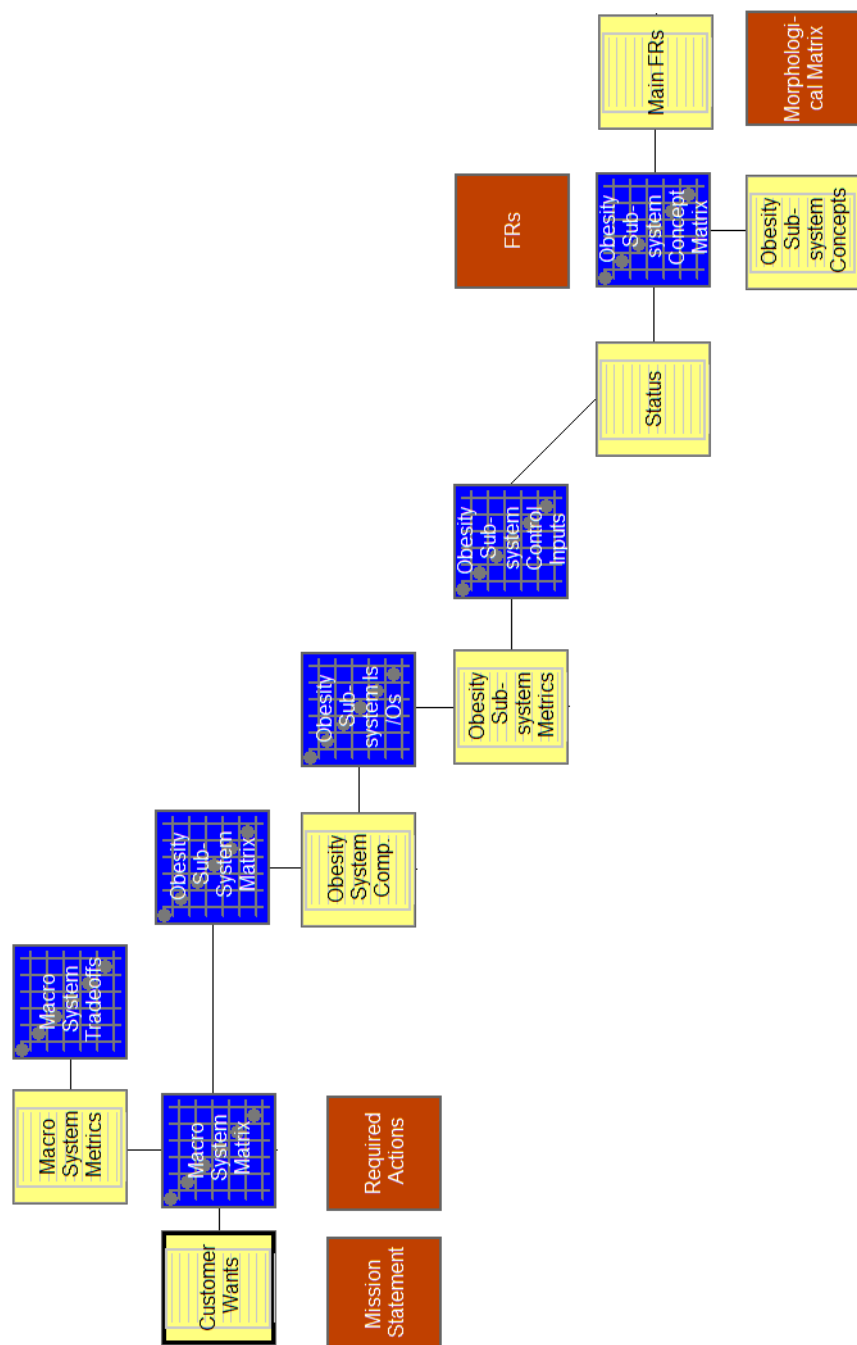


Figure 71 - System/Subsystem Development QFD

- (cont.) The need for a new QFD data is reduced when developing a new system as some information can be reused. System thinking is used in the development of a new subsystem, directly from the higher level system. For example, if a subsystem to prevent blood pressure issues in patients is developed, the system level “house” (HOQ1) is not changed. This is a very important characteristic of the approach as it guarantees alignment of the solutions to the common goal of prevention.

The prevention subsystems (i.e., obesity, blood pressure, diabetes, etc.) attempt to communicate horizontally and continuously optimize through the optimization of the system goal. Moreover, there is a real incentive for “vertical” communications, especially if the subsystems are not build simultaneously, which is the case for this research.

Some of the reasons that the subsystems will naturally cooperate for a better performance include:

- The subsystems are not competing since they share the same overall goal which includes the goal of the system.
- If the subsystems are not developed simultaneously, there is a great benefit in understanding how the previously designed subsystem was developed. The reason this is beneficial, especially when considering this integrated way of using the QFD, is because there will be many similarities if they have the same overall goal.

As an example, if the intent is to develop a prevention subsystem for dealing with a high-blood pressure condition after the obesity subsystem, beyond the commonality of the HOQ1 (i.e., the prevention system), there will be many similarities even in the



subsequent resulting houses and potentially within the development of the final, more specific solution.

### 7.2.3. Systems Dynamics Modeling of the Obesity Model

The main contribution introduced by this research is the fact that obesity can be viewed as a dynamic and complex system, and modeled accordingly. There are a variety and often competing and conflicting approaches to solving the obesity problem. Some are listed below but there are different variations of each, as follows:

- Dieting programs – Are probably the most commonly known and used methods for attempting to solve the problem
- Physical activities – Arguably next to dieting as the most used and misused method of losing weight
- Bariatric surgery – Invasive procedure that requires permanent monitoring of the patient for the rest of their lives
- Focused groups – Can include organizations such as “Weight Watchers” and “The Biggest Loser”, where believing in a team approach of weight loss is emphasized

The reality is that none are incorrect choices, but none of them can solve the problem without some intervention relying on the other alternatives. In fact, the obesity problem continues becoming larger as a result of all the consequences outlined at the beginning of this research.

The approach used in this research is to consider each individual as a unique entity with different characteristics, beliefs, needs, socio-economic position, etc. Moreover, the research considers that there are various ways to motivate different

individuals, even if all conditions appear to be similar. There are other parameters that need to be considered and become part of the solution.

Therefore, the researcher believes that an integrated system dynamics approach is the most promising. In this way, the individual becomes an inherent part of the solution and continuously interacts with the strategy. In fact, the obese as well as the people that just want to maintain a healthy weight are able to create their own strategy based on their very distinct characteristics and personal preferences.

In a holistic way, the individuals become the managers of their health of which they take ownership. In the opinion of the researcher, this not only has the potential of solving the problem for a certain individual, but more importantly, to deal with the problem effectively at the population level.

### 7.3. Limitations and Future Work

The limitations of this research emerge from an array of opportunities for which the current situation of the healthcare system brings into perspective. Some details on limitations include the following:

- Obesity is one of several the preventable diseases. Even finding a reasonable solution to the obesity pandemic will not yet create a robust prevention system. It is necessary to have many, if not all, of the preventable diseases addressed to build a realistic and comprehensive preventive system. A possible future work direction is the replication of the methodology proposed by this work in other preventable conditions.

- Although captured during the system design phase, many important elements are not incorporated in the final solution. Particularly, the Non-physical factors are not included. While some probably play a major role in the process of weight loss, others may be critical components for the sustainability of an obesity control strategy. The researcher plans to address this set of factors, as well as others not considered here, in a future research effort.
- The human body is most likely one of the most complex systems in nature. While attempts to simulate it are always challenging, the model developed through this research has certain merits in accurately following the real change in body mass from real life data. However, the sample data supplied by the weight loss professionals have certain unique characteristics, making it easier to simulate the weight loss progress. First and foremost, the patients were under specialists' advisory, within a special program that allowed for an aggressive approach with quite remarkable short term results. This most likely helped to maintain high motivation among the patients and contributed to more accurate reporting. In reality, a universal solution to obesity must allow for individual effort and freedom, independent of the specialist's supervision in most cases. How well the model is able to simulate the human body behaviour and how to improve its accuracy in less controlled environments, needs to be further investigated through future research.
- QFD is a technique that neither assures convergence nor provides solutions on its own. QFD is a systematic system design concept that initially is qualitative in nature before using analytics for moving through the design process. This

means that the VoC cannot be captured by a mathematical formula, although it can be “translated” and quantified to a certain degree. Moreover, it is very dependent on the way stakeholders are defined, and it is continuously transforming with changes in the customers. Therefore, it is rather difficult to assess the effectiveness of QFD before actually implementing the system. As a proposed future work, the system needs to be implemented, even on a limited scale, and the efficiency must be evaluated. There will most likely be a set of iterations, common in system design, until an optimum system will be identified in order to be implemented at a larger scale.

- One of the critical elements of system design that emerges from the use of QFD methodology is identification of the conflicting trends among the CTSs, as well as FRs. While identification is important, it is also important to address them so that the system robustness improves. Other system design concepts need to be employed for achieving this state (e.g., Axiomatic Design, Theory of Inventive Problem Solving (TRIZ), etc.). This will be addressed in future work.
- The data used for model verification was real life data, not initially collected by the data provider for purpose defined in this thesis. While the model provides a very good fit once verified with the real life data, there is no guarantee for the expendability to more general weight loss programs. A more comprehensive data acquisition process needs to be employed in order to further understand the limitations of the model.

- The amount of data was limited to what was provided by the specialized clinic. Identifying other sources of data, or alternately, designing experiments and developing a research specific database is the goal of a future work.
- System Dynamics modeling and approach is generally suitable for modeling complex systems. SD is attempting to deal with higher level problems, and is dealing with incomplete data. It can also model qualitative types of information with a main focus on the system's behaviour, rather than an increased accuracy by simplifying the assumptions. Therefore, the precision and its ability to model discrete events are sometimes not as good as other simulation methods. This is something to consider once the step from modeling the weekly weight progression to smaller increments (e.g., daily, hourly) is made in future research.
- It was difficult finding transfer functions (mathematical equations) for many of the outputs in the design process that became the inputs to the modeling effort. The current model is based on three major equations, supported by other dependent functions, as well as personal characteristics. The model behaves well with a fit of over 90%. However, in an uncontrolled environment that was not tested as part of this research work, the lack of analytical data might fundamentally affect the accuracy of the model. As a future opportunity, more transfer functions need to be identified for the remaining parameters. Moreover, if they do not exist (e.g., motivation related to obesity, stress related to obesity, etc.) they will need to be developed.

## APPENDICES

### APPENDIX A

#### Perceived Stress Test

The questions in this scale ask you about your feelings and thoughts during the last month. In each case, the individual is asked to indicate *how often* you felt or thought a certain way. Although some of the questions are similar, there are differences between them and you should treat each one as a separate question. The best approach is to answer each question fairly quickly. That is, do not try to count the number of times you felt a particular way, but rather indicate the alternative that seems like a reasonable estimate.

Table 16 – Perceived Stress test						
	In the last month, how often have you	Never	Almost	Some-	Fairly	Very
1.	... been upset because of something that	0	1	2	3	4
2.	... felt that you were unable to control	0	1	2	3	4
3.	... felt nervous and “stressed”?	0	1	2	3	4
4.	... dealt successfully with irritating life	0	1	2	3	4
5.	... felt that you were effectively coping	0	1	2	3	4
6.	... felt confident about your ability to	0	1	2	3	4
7.	... felt that things were going your	0	1	2	3	4
8.	... found that you could not cope with	0	1	2	3	4

9.	... been able to control irritations in	0	1	2	3	4
10.	... felt that you were on top of things?	0	1	2	3	4
11.	... been angered because of things that	0	1	2	3	4
12.	... found yourself thinking about things	0	1	2	3	4
13.	... been able to control the way you	0	1	2	3	4
14.	... felt difficulties were piling up so	0	1	2	3	4

## APPENDIX B

### Behavioural Regulation in Exercise Questionnaire

Please indicate the extent to which each of the following statements is true for you by circling the number corresponding to your choice.

Table 17 – Behavioural Regulation in Exercise Questionnaire

		Not true for me		Some- times true for me		Very true for me
1.	I exercise because other people say I should.	0	1	2	3	4
2.	I value the benefits of exercising.	0	1	2	3	4
3.	I exercise because it is fun.	0	1	2	3	4
4.	I feel guilty when I do not exercise.	0	1	2	3	4
5.	I take part in exercise because my friends, family, or partner says that I should.	0	1	2	3	4
6.	It is important to me to exercise regularly.	0	1	2	3	4
7.	I enjoy my exercise sessions.	0	1	2	3	4
8.	I feel ashamed when I miss an exercise session.	0	1	2	3	4
9.	I exercise because others will not be pleased with me if I do not.	0	1	2	3	4
10.	I think it is important to make the effort to exercise regularly.	0	1	2	3	4
11.	I find exercise a pleasurable activity.	0	1	2	3	4



12.	I feel under pressure from my friends/family to exercise.	0	1	2	3	4
13.	I feel like a failure when I have not exercised in awhile.	0	1	2	3	4
14.	I exercise primarily for health reasons.	0	1	2	3	4
15.	I get restless if I do not exercise regularly.	0	1	2	3	4
16.	I get pleasure and satisfaction from participating in exercise.	0	1	2	3	4

## APPENDIX C

### Additional Causal relationships

As mentioned in Chapter III, there is a sequential approach to building a reliable and accurate model. The three main causal relationships presented in the previous sub-chapter cover important components of the structural model. However, there are many other components that are not accounted for so they are part of the “unknown”, at this point, variation.

In the next few paragraphs several other causal relationships identified in the scientific literature are presented. They cover other components of the structural model that will be addressed in the future. As a general note, there is no abundance of literature containing analytical studies related to obesity (e.g. developing comprehensive multivariate, and multiparameter models that can be used for prediction). There is a lot of empirical evidence obtained either by trial and error or other unreliable methods.

At this point in time, unless more evidence becomes available, in spite of the fact that there are many components of the structural model covered by the literature, the researcher believes that in some instances, experimental design needs to be employed to develop analytical evidence. Particularly, in the psychological area of the structural model, there is need for analytical evidence linking mathematically various aspect of obesity with the psychological behaviour. Yet obvious barriers, mostly ethical, to conducting such experiments, exist.

In order to minimize the content of the dissertation, the additional causal relationships are not elaborated beyond just presenting the main outcome. Moreover, the

constants used are not presented. If the reader needs to obtain more detailed information, the author of this dissertation can be contacted or the reader can go directly to the respective research as all the evidence used is part of the bibliography.

#### Woodruff et al

The followings are examples of the Estimated Energy Requirement (*EER*) and Total Energy Expenditure (*TEE*) causal relationships for the male and the female from the paper (Woodruff, Hanning, & Barr, 2008) by Woodruff, Hanning & Barr.

*EER* - Male:

$$EER = TEE + EnergyDeposition$$

$$EER = 88.5 - 61.9 \times Age[years] + PA \times (26.7 \times Weight[Kg] + 903 \times Height[m] + 20(or\ 25)) \quad (27)$$

*EER* - Female:

$$EER = TEE + EnergyDeposition$$

$$EER = 135.3 - 30.8 \times Age[years] + PA \times (10.0 \times Weight[Kg] + 934 \times Height[m] + 20(or\ 25)) \quad (28)$$

*TEE* - Male:

$$TEE = -114 - 50.9 \times Age[years] + PA \times (19.5 \times Weight[Kg] + 1161.4 \times Height[m]) \quad (29)$$

*TEE* - Female:

$$TEE = 389 - 41.2 \times Age[years] + PA \times (15.0 \times Weight[Kg] + 701.6 \times Height[m]) \quad (30)$$

(Gerrior, Juan, & Basiotis, 2006) list several causal relationships for Basal Energy Expenditure, PAL and TEE.

For men:

$$BEE = 293 + 3.8 \times age \text{ (years)} + 456.4 \times height \text{ (meters)} + 10.12 \times weight \text{ (kg)} \quad (31)$$

For women:

$$BEE = 247 + 2.67 \times age \text{ (years)} + 401.5 \times height \text{ (meters)} + 8.6 \times weight \text{ (kg)} \quad (32)$$

The next step is the calculation of the impact of each reported physical activity on energy expenditure ( $\Delta$  PAL). This formula is as follows:

$$\Delta \text{ PAL} = \frac{(\text{MET}_s - 1) \times \left[ \left( \frac{1.15}{0.9} \right) \times \text{Duration (minutes)} \right] / 1440}{BEE / [0.0175 \times 1440 \times \text{weight (kg)}]} \quad (33)$$

*MET* – metabolic equivalents

After the  $\Delta$  PAL is calculated for each physical activity, the physical activity category (*PAL*: sedentary, low active, active, or very active) is determined based on the basal activity impact on energy expenditure (a factor of 1.1) and the sum of all activities (sum of  $\Delta$  PAL). This factor accounts for the thermic effect of food (*TEF*) and post-exercise increase in energy expenditure.

*TEE* for men:

$$TEE = 864 + 9.72 \times age \text{ (years)} + PA \times [(14.2 \times weight \text{ (kg)} + 503 \times height \text{ (meters)})] \quad (34)$$

*TEE* for women:

$$TEE = 387 - 7.31 \times age (years) + PA \times [(10.9 \times weight (kg) + 660.7 \times height (meters))] \quad (35)$$

### Flatt

(Flatt J. P., 2007), proposed causal relationships for the Basal Energy Expenditure (*BEE*) and Percentage Body Fat (*%BF*):

Female *BEE*:

$$fBEE = 247 - 2.67 \times age (years) + 8.60 \times weight (kilograms) + 401.5 \times height (meters); R^2 = 0.62 \quad (36)$$

Male *BEE*:

$$mBEE = 293 - 3.8 \times age (years) + 10.12 \times weight (kilograms) + 456.4 \times height (meters); R^2 = 0.63 \quad (37)$$

where *fBEE* and *mBEE* stand for *BEEs* in terms of kilocalories per day in women and men, respectively.

*%BF* in women:

$$\%BF = 1.4303 + 1.1735 \times BMI, R^2 = 0.77 \quad (38)$$

*%BF* in men:

$$\%BF = -4.3422 + 0.9921 \times BMI, R^2 = 0.55 \quad (39)$$

### Schutz et al

(Schutz & Hunter, 2001) developed causal relationships related to different factors related to obesity. Relationships among different parameters are listed below:

$$AEE = TEE \left( \frac{kcal}{d} \right) - REE \left( \frac{kcal}{d} \right) \quad (40)$$

*AEE* – Activity energy expenditure (kcal/d); *REE* – Resting energy expenditure

Definition: Activity-related EE. Application: Useful for energy-balance studies to calculate energy requirements due to physical activity using an objective assessment of *TEE*.

$$PAL_{EE} = \frac{TEE \left( \frac{kcal}{d} \right)}{REE \left( \frac{kcal}{d} \right)} \quad (41)$$

*PAL<sub>EE</sub>* – Physical activity level (ratio)

Definition: Index of physical activity-related *EE* over typical 24-h period.

Application: Enables comparisons of average daily physical activity *EE* levels among individuals or populations.

$$MET_{EE} = \frac{VO_2 \text{ activity } \left( \frac{mlO_2}{kgmin} \right)}{3.5 \frac{mlO_2}{kgmin}} \quad (42)$$

*MET<sub>EE</sub>* – Metabolic equivalent (ratio)

Definition: Relative intensity of a specific physical activity performed in the steady state. Application: Useful for describing intensities of various activities and for prescribing physical activities to patients.

$$PAR_{EE} = \frac{EE \text{ activity } \left( \frac{kcal}{min} \right)}{REE \left( \frac{kcal}{min} \right)} \quad (43)$$

*PAR<sub>EE</sub>* – Physical activity ratio

Definition: Per-minute energy cost of specific activity, relative to per-minute *REE*

Application: Enables comparisons of energy costs of tasks performed by different persons.

$$ARTE_{EE} = \frac{TEE \left( \frac{kcal}{d} \right) \times 0.9 - REE \left( \frac{kcal}{d} \right)}{reference\ activity \left( \frac{kcal}{min} \right) - REE \left( \frac{kcal}{min} \right)} \quad (44)$$

$ARTE_{EE}$  – Activity related time equivalent (Min/d)

Definition: Index of amount of time spent at  $EE$  level equivalent to that of reference activity. 0.9 provides adjustment for average thermic effect of food (10%).

Application: Enables comparisons of duration of physical activity between subjects who have different energy costs of movement due to differences in body mass and/or energy economy of exercise.

$$HR_{net} = (daily\ average\ HR \left[ \frac{beats}{min} \right] - resting\ HR \left[ \frac{beats}{min} \right]) \times 1440 \left( \frac{min}{d} \right) \quad (45)$$

$HR$  – Heart rate

Definition: Measure of above-rest HR response to free-living activities.

Application: Enables comparisons of average above-resting HR level and related EE of free-living activities.

$$PAR_{HR} = \frac{HR\ activity \left( \frac{beats}{min} \right)}{HR\ resting \left( \frac{beats}{min} \right)} \quad (46)$$

$PAR$  – Physical activity ratio

Definition: Measure of cardiac response to selected activities as a multiple of resting  $HR$ . Application: Enables comparisons of relative  $HR$  responses of subjects to various activities.

### Cunningham

A claim of a more accurate resting energy expenditure ( $REE$ ) equation was made (Cunningham, 1991), which proposed a generalized prediction equation. It explains 65-

90% of the variation in *REE*. Several studies suggest, further, that *FFM* predicts total daily energy expenditure (*IDEE*) equally well.

$$REE = 370 + 21.6 \times FFM \quad (47)$$

FFM – Fat-free mass

### Flatt

Causal relationships examining the percentage of body fat (*%BF*) were developed by Flatt in (Flatt J. , 2004). It also used SD to generate a model and examine how the interactions between carbohydrate and fat metabolism influence body weight regulation.

To evaluate the relative impacts of various parameters on the *%BF* for which steady states would become established, the results of 33 such model runs were examined by multiple regression analysis, with *% BF* as the dependent variable. This led to the following equation ( $\pm$  Standard Error (SE) in parenthesis):

$$\begin{aligned} \%BF = & 3.13 + 8.00 (\pm 0.95) \times FCR + 0.64 (\pm 0.08) \times \%diFat + \\ & 0.10 (\pm 0.02) \times Palat - 10.3 (\pm 2.2) \times PAL \end{aligned} \quad (48)$$

N = 33 and R<sup>2</sup> = 0.80 (p < 0.0001 for all parameters).

Palat = Palatability

FCR = fat-CHO ratio

CHO - carbohydrate

The prediction was improved when mean Glycogen (GLY) was used instead of palatability and PAL:

$$\begin{aligned} \%BF = & 93.8 + 9.57 (\pm 0.55) \times FCR + 0.62 (\pm 0.04) \times \%diFat + \\ & 0.237 (\pm 0.016) \times meanGLY \end{aligned} \quad (49)$$



$N = 33$  and  $R^2 = 0.94$  ( $p < 0.0001$  for all parameters).

Sutton et al.

In (Sutton, Logue, Jarjoura, Baughman, Smucker, & Capers, 2001) the authors describe a multi-item algorithm of SOC (M-SOC) for weight loss-related behaviours that attempts to overcome some of the conceptual and methodological difficulties encountered in previously SOC assessments. The Energy Expenditure and Energy Intake are plotted against a Likert scale of the State of Change from 1-Contemplating (weight loss) to 5-Maintenance.

Slevin et al.

(Slevin, 2004) found that high intensity counselling or behavioural interventions and pharmacological interventions could result in moderate weight loss. Authors' conclusions were that counselling or behavioural interventions and pharmacotherapy can result in moderate weight loss (approximately 3 to 5 kg) over at least 6–12 months.

Rutters et al.

In (Rutters, Nieuwenhuizen, Lemmens, Born, & Westerterp-Plantenga, 2008) investigated the effect of acute psychological stress on food intake, using the eating in the absence of hunger paradigm, in normal and overweight men and women, taking dietary restraint and disinhibition into account. Acute psychological stress, indicated as an increase in state anxiety and POMS scores, was related to an increase in energy intake in the absence of hunger in adults. Moreover, subject-specific features including higher trait

anxiety scores, were related to a larger increase in state anxiety scores during the stress condition.

#### Cohen et. al.

In (Cohen, Kamarck, & Mermelstein, 1983) the authors claim that it is a common assumption among health researchers that the impact of "objectively" stressful events is, to some degree, determined by one's perceptions of their stressfulness. Data are presented on the psychometric properties of the Perceived Stress Scale (PSS) – Appendix A, an instrument developed in response to these issues. The PSS measures the degree to which situations in one's life are appraised as stressful.

There are some clear advantages to objective measures of stressful events. First, such measures permit an estimate of the increased risk for disease associated with the occurrence of easily identifiable events. Second, the measurement procedure is often simple. Third, these measurement techniques minimize the chance of various subjective biases in the perceptions and reporting of events.

The 14 items of the PSS are presented in Appendix A. PSS scores are obtained by reversing the scores on the seven positive items. E.g. 0=4, 1=3, 2=2, 3=1, and then summing across all 14 items. Items 4, 5, 6, 7, 9, 10 and 13 are the positively stated items.

#### Mullan et. Al.

In (Mullan, Markland, & Ingledew, 1997) the authors developed a behavioral Regulation in Exercise Questionnaire (BREQ) to measure external, introjected, identified, intrinsic and amotivated forms of regulation for exercise behavior. In organismic

integration theory (OIT), another sub-theory of self-determination theory, OIT is concerned with the process by which individuals come to regulate acts, which are not initially intrinsically interesting by transforming regulation, by external contingencies into regulation by internal processes. OIT outlines several forms of behavioral regulation: external, introjected, identified, and integrated, which manifest varying degrees of self-determination and are best placed on a continuum ranging from non-self-determined to completely self-determined motivation.

Behavior, which is externally regulated, is undertaken purely to avoid immediate negative consequences, typically administered by another. In the case of exercise this would represent the "I exercise because I am told to" approach, and represents non-self-determined regulation. Introjected regulation of behavior follows internalization of external control that is then applied to the self through the administration of sanctions, pressures and other self-controlling behaviors. In this case, "I'll feel guilty if I don't" might be given as a reason for exercising. Action undertaken because of its value, importance or usefulness to the individual is evidence of identified regulation. Finally, when the regulatory process is fully integrated within the individual's sense of self, regulation is completely autonomous and known as integrated regulation; behavior is undertaken willingly and with no sense of coercion. Integrated regulation is, consequently, very similar to the concept of intrinsic motivation that also represents fully self-determined regulation. A BREQ template is attached to Appendix B.

## APPENDIX D

### Model Results and Validation

Table 18 - Real life data structure

EI1-M38	W1-M38	W1-M38-k	OMW1-M38	EI2-F39	W2-F39	W2-F39-k	OMW2-F39	EI3-M39	W3-M39	W3-M39-k	OMW3-M39	EI4-M41	W4-M41	W4-M41-k
500	273.00	123.831	120.11	500	310	140.614	137.850	500	330	149.685	146.360	500	390.0	176
500	262.00	118.841	117.77	500	305	138.346	135.610	500	321	145.603	143.670	500	371.0	168
500	253.50	114.986	114.93	500	294	133.356	132.890	500	307	139.253	140.390	500	365.5	165
500	247.25	112.151	112.57	500	289	131.088	130.630	500	301	136.531	137.680	500	356.0	161
500	242.50	109.996	109.86	500	285	129.274	128.040	500	295	133.810	134.560	500	348.0	157
500	240.00	108.862	107.68	500	280	127.006	125.950	500	288	130.635	132.060	500	342.0	155
				800	278	126.099	126.099	800	286	129.727	129.727	500	338.0	153
				800	277	125.645	123.920	800	282	127.913	127.080	800	341.5	154
				800	275	124.738	122.130	800	280	127.006	124.900	800	338.0	153
				1000	274	124.284	124.280	1000	277	125.645	125.645	800	338.0	153
				1000	273	123.831	122.370	1000	274	124.284	123.290	1100	341.0	154
				1000	273	123.831	120.760	1000	273	123.831	121.340	1100	343.0	155
				500	279	126.552	124.020	500	273	123.831	123.830			
				500	270	122.470	121.970	500	265	120.202	121.010			
				500	264	119.748	119.480	500	260	117.934	118.510			
				500	256	116.120	117.410	500	254	115.212	115.810			
				500	252	114.305	115.040	500	249	112.945	113.290			
				500	249	112.945	113.120	500	246	111.584	110.730			
				500	246	111.584	110.880							

Table 19 – All Data used for Regression

↓	C1-T	C2	C3	C4	C5-T	C6	C7	C8	C9-T	C10	C11
	Subjects	Actual	Simulated		Subjects_1	Actual_1	Simulated_1		Subjects_1_1	Actual_1_1	Simulated_1_1
1	GB	106.400	106.400		W2-F39-k	126.552	124.020		W4-M41-k	155.129	156.940
2	GB	104.700	105.200		W2-F39-k	122.470	121.970		W4-M41-k	153.314	153.580
3	GB	103.800	104.000		W2-F39-k	119.748	119.480		W4-M41-k	154.902	154.902
4	GB	103.300	103.210		W2-F39-k	116.120	117.410		W4-M41-k	153.314	151.840
5	GB	103.000	102.330		W2-F39-k	114.305	115.040		W4-M41-k	153.314	149.340
6	GB	102.700	102.250		W2-F39-k	112.945	113.120		W4-M41-k	154.675	154.675
7	GB	100.300	101.080		W2-F39-k	111.584	110.880		W4-M41-k	155.582	151.960
8	GB	101.000	100.150		W3-M39-k	149.685	146.360		W5-M68-k	117.934	115.420
9	GB	99.900	99.530		W3-M39-k	145.603	143.670		W5-M68-k	114.305	113.000
10	GB	97.400	98.590		W3-M39-k	139.253	140.390		W5-M68-k	110.223	110.660
11	GB	97.800	98.710		W3-M39-k	136.531	137.680		W5-M68-k	107.048	108.210
12	GB	96.700	96.920		W3-M39-k	133.810	134.560		W5-M68-k	104.326	106.010
13	W1-M38-k	123.831	120.110		W3-M39-k	130.635	132.060		W5-M68-k	103.873	103.873
14	W1-M38-k	118.841	117.770		W3-M39-k	129.727	129.727		W5-M68-k	103.873	101.830
15	W1-M38-k	114.986	114.930		W3-M39-k	127.913	127.080		W5-M68-k	103.419	100.050
16	W1-M38-k	112.151	112.570		W3-M39-k	127.006	124.900		W5-M68-k	103.873	103.873
17	W1-M38-k	109.996	109.860		W3-M39-k	125.645	125.645		W5-M68-k	103.419	102.100
18	W1-M38-k	108.862	107.680		W3-M39-k	124.284	123.290		W5-M68-k	103.419	100.420
19	W2-F39-k	140.614	137.850		W3-M39-k	123.831	121.340		W6-M50-k	97.976	95.690
20	W2-F39-k	138.346	135.610		W3-M39-k	123.831	123.830		W6-M50-k	96.388	93.490
21	W2-F39-k	133.356	132.890		W3-M39-k	120.202	121.010		W6-M50-k	95.708	91.360
22	W2-F39-k	131.088	130.630		W3-M39-k	117.934	118.510		W6-M50-k	93.894	89.140
23	W2-F39-k	129.274	128.040		W3-M39-k	115.212	115.810		W6-M50-k	92.079	87.170
24	W2-F39-k	127.006	125.950		W3-M39-k	112.945	113.290		W6-M50-k	91.626	91.626
25	W2-F39-k	126.099	126.099		W3-M39-k	111.584	110.730		W6-M50-k	90.265	89.750
26	W2-F39-k	125.645	123.920		W4-M41-k	176.901	173.130		W6-M50-k	91.172	87.970
27	W2-F39-k	124.738	122.130		W4-M41-k	168.283	170.080		W6-M50-k	90.492	90.492
28	W2-F39-k	124.284	124.280		W4-M41-k	165.788	166.370		W6-M50-k	89.584	88.840
29	W2-F39-k	123.831	122.370		W4-M41-k	161.479	163.310		W6-M50-k	88.904	87.290

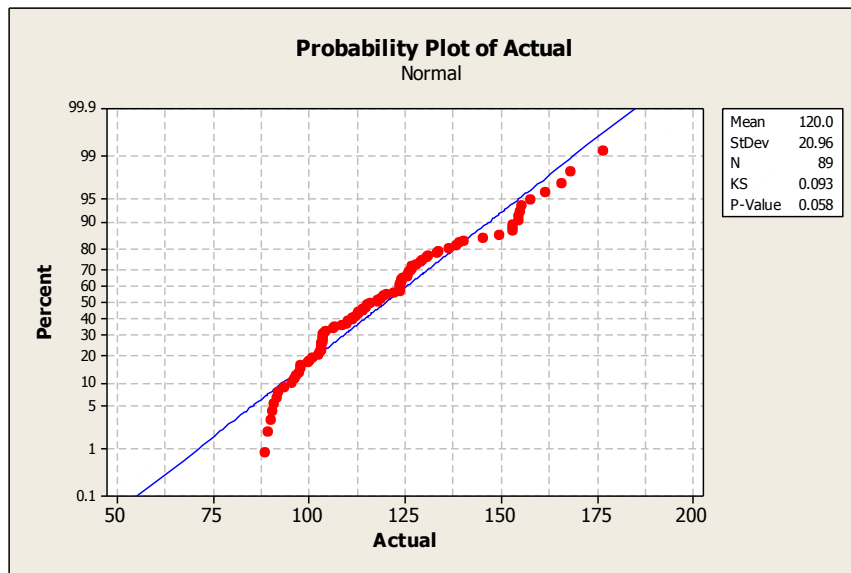


Figure 72 – Normality Plot for Actual

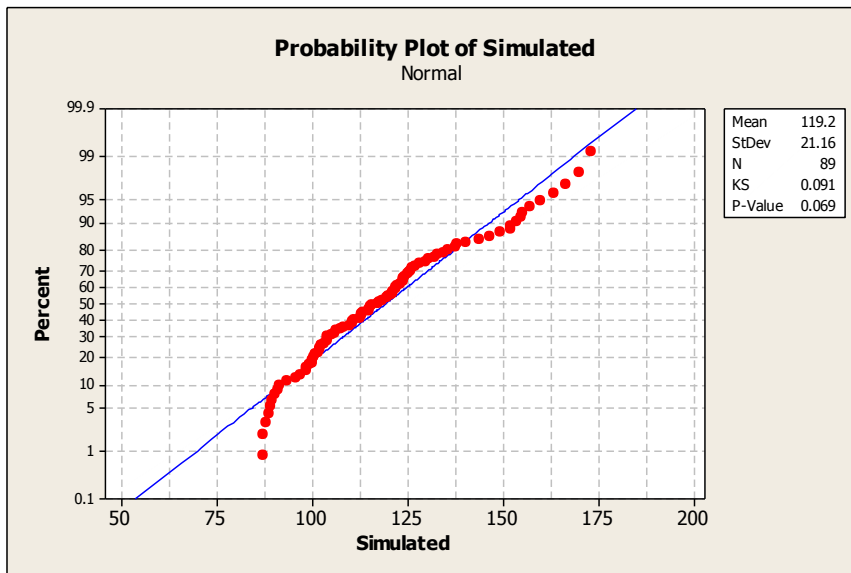


Figure 73 – Normality Plot for Simulated

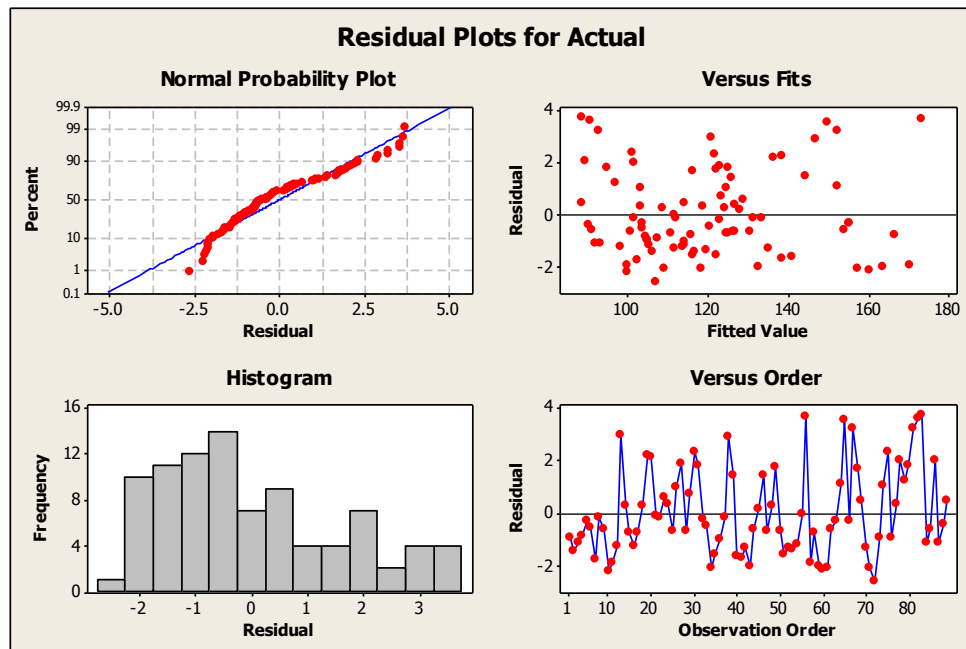


Figure 74 – Residual Plots for Actual

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Zelick, P. R. (2007). *Issues in The Psychology of Motivation*. New York, NY: Nova Science Publishers, Inc.

## VITA AUCTORIS

NAME: Gheorghe Mugur Bacioiu  
PLACE OF BIRTH: Bucharest, Romania  
YEAR OF BIRTH: 1968  
EDUCATION Ion Luca Caragiale High School, Ploiesti, Romania  
1982-1986  
Universitatea Politehnica Bucharest, Bucharest, Romania  
1988-1993 B.Sc.-M.Sc.  
University of Windsor, Windsor, Ontario  
2007-2012 PhD